The development of a design for changeover (DFC) methodology

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Award date:
2007

Awarding institution:
University of Bath

The Development of a Design for Changeover (DFC) Methodology

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A thesis submitted for the degree of Doctor of Philosophy
University of Bath
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March 2007

Abstract

A rapid changeover capability is central to today's thinking in respect of responsive, small batch manufacturing. Mass customization and other modern manufacturing paradigms have prompted companies to adapt swiftly to market turbulence and at the same time avoid the traditionally high unit costs associated with custom-made or small-volume products.

To support rapid and high quality changeover, global changeover improvement opportunities are assessed and a contextual framework is developed. This is referred to as the 4P framework. The framework differentiates between various areas (People, Practice, Products and Process) in which improvement can be sought and helps in balancing improvement efforts.

Historically, an operations-focused approach has been adopted in reducing changeover times; however, it is argued that there is a significant benefit if there is a stronger focus on equipment and system design. There is a considerable challenge to design and build cost-effective changeover-capable equipment. A number of methodologies for the design of changeable manufacturing systems have been proposed in the literature. Although they can be used to generally guide design, they lack systematic techniques to benchmark design alternatives. As a result machine designers have often no other option as to design 'changeoverability' on an *ad hoc* basis.

A systematic DFC methodology which builds upon existing DFX and other engineering design methodologies is proposed in this thesis. Various techniques to benchmark changeover capabilities of equipment design are also proposed. The generic DFC methodology combines the evaluation of changeover capabilities and the identification of improvement possibilities. Three detailed case studies utilising the proposed methodology are presented. These case studies show the effectiveness of the proposed techniques to evaluate and improve changeover performance of manufacturing equipment from the outset.

Acknowledgements

Thanks are due to my joint project supervisors, **Prof Steve J Culley**, **Prof Anthony R Mileham** and **Dr Geraint W Owen**, for their commitment and guidance during the course of this research.

I would like to express my sincerest thanks to my colleague **Dr Richard McIntosh**, who was always available for intense discussions throughout the project. I am grateful for his valuable input.

A number of graduate students have worked on or with DFC throughout my three years at the IMRC. I would like to thank, **Tim Ostle**, **Augusto Bado**, **Alex Moorhouse**, **Dorcas Chan** and **Dean Gale** for their work during their final year projects.

The work has also been supported by a number of industrial companies and engineers. The author gratefully acknowledges this support and expresses his thanks for the advice and support of all concerned.

I would also like to thank my friends and colleagues at the University of Bath. They all helped to make my time in Bath a truly unique experience.

Sincerest thanks are also due to my family, in particular my parents, for all their generous support throughout the years. Thank you!

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1 Introduction

Modern manufacturing is driven by many factors, including an increasing need to satisfy customer demands for greater product variety and for more responsive, small batch delivery. Manufacturing system flexibility is important if companies want to successfully compete in these market conditions. It has been reported that rapid and high quality process changeovers greatly assist in providing the manufacturing flexibility and responsiveness that customers now demand (Spencer and Guide, 1995, Tu *et al.*, 2004, Bicheno, 2003, Prasad, 1995). The role of changeover is cemented in the established modern manufacturing paradigms of just-in-time *(Golhar and Stamm, 1991, Nakamura et al.*, 1998, Prasad, 1995) and lean (Bicheno, 2003) and is additionally recognised in the emerging manufacturing paradigm of mass customisation and product personalisation (Pine, 1993, Urbani *et al.*, 2003, McCarthy, 2004, Reik *et al.*, 2005b, Montreuil and Poulin, 2005). The customer-driven mass customisation paradigm seeks to satisfy market demands particularly in terms of product individualisation and ready delivery. Changeover capability is prominent in such a time-based manufacturing environment, where successful companies have to be able to adapt swiftly to market turbulence and at the same time avoid the traditionally high unit costs associated with custom made or small volume products. Frequent switching of manufacture between different products and processes while minimising the detriment to overall productivity and quality is central to these aims.

A changeover is the process of transforming manufacturing equipment from the manufacture of one product to another. During this process certain elements of the manufacturing hardware, such as tooling and work holding fixtures, need to be changed and/or other settings carried out in order to manufacture the new product at set quality and output rates (Shingo, 1985, McIntosh *et al.*, 2001). Historically, attempts to avoid the production losses associated with changeovers have favoured long production runs and a minimal degree of product variety (Womack *et al.*, 1990).

Changeover improvement has been a focus of attention for a number of years as the limitations of systems developed for the mass-manufacturing paradigm have become recognised. Shingo's defining work to create the SMED (Single Minute Exchange of Die) methodology (Shingo, 1985) has been interpreted and developed into a variety of training and implementation strategies by practitioners and consultancies (McIntosh, 1998). However, the methodology is always seen to retain a core objective of translating changeover tasks into external time and improvement by revising working and operational procedures is the main emphasis (McIntosh *et al.*, 2001). In doing so, the methodology can undervalue opportunities to modify process equipment (McIntosh *et al.*, 2000).

Even though a number of case studies and examples of good design practice can be found from the literature there is no formal design for changeover (DFC) methodology. Some design for changeover rules have been proposed (McIntosh, 1998, Van Goubergen and Van Landeghem, 2002), which can be used to generally direct equipment design. However, these design rules do not give full guidance since they do not provide means to assess what new equipment's changeover capabilities will be once in service. Equally the rules are unranked, where some rules will be liable to have a far greater impact.

Thus machine designers have no option but to develop a changeover capability based on their experience, effectively on an *ad hoc* basis as there is no coherent, structured guidance as to how genuine rapid changeover performance may be incorporated at the design stage.

1.1 Research Hypotheses

Following a thorough literature and case study based assessment of current practice the research presented in this thesis addresses two key gaps identified in the literature. One is the overall classification of changeover improvement options. The second area is the lack of a formal Design for Changeover methodology, which would assist equipment designers in considering changeover issues while designing manufacturing equipment.

Regarding the two research areas which have been identified, the following research hypotheses are proposed:

Hypotheses 1: A framework can be developed which encompasses changeover improvement as part of retrospective improvement as well as new equipment design. The framework can be developed to identify and classify global areas where changeover improvement can be sought.

Hypotheses 2: A formal and generic Design for Changeover (DFC) methodology can be formulated and validated which provides design guidance for equipment designer.

Chapter 3 will translate these hypotheses into detailed aims and objectives, which are addressed in later sections of this thesis.

1.2 Associated Work at the University of Bath

The presented work has been funded by the Engineering and Physical Science Research Council (EPSRC) and was carried out at the Engineering Innovative Manufacturing Research Centre (IMRC) at the University of Bath. Two researchers were engaged on the three year project on Design for Changeover together with significant assistance from staff at the University of Bath and collaborating companies.

The research project aimed to identify the design elements that constitute and facilitate changeovers in a variety of areas and domains. Within this the author's own research focus was the design of manufacturing equipment with high changeover performance. The research of the author's senior colleague, Dr Richard McIntosh, was the integration of design for changeover into Mass Customisation and the area of product design for changeover.

Much of the collaborative work with industry, on which the case studies presented in this thesis are based, has been carried out by the author in conjunction with his colleague, Dr Richard McIntosh. A review of the history of research on the topic of changeover improvement at the University of Bath is given in Chapter 4.

1.3 Outline

The underlying structure of this thesis consists of five main sections, namely setting the scene, state of the art and critique, the author's contribution, validation of developed methodology and conclusions and future work. Figure 1.1 illustrates how the different chapters correspond with this thesis structure.

The main part of the thesis (Chapters 4 – 10) is split into two strands, each strand addressing one of the hypotheses proposed previously. Chapters 4 and 5 focus on the research area of global changeover improvement opportunities and chapters 6-10 describe the development of a formal Design for Changeover (DFC) methodology. Relevant literature can be found in both areas and these are separately reviewed and discussed.

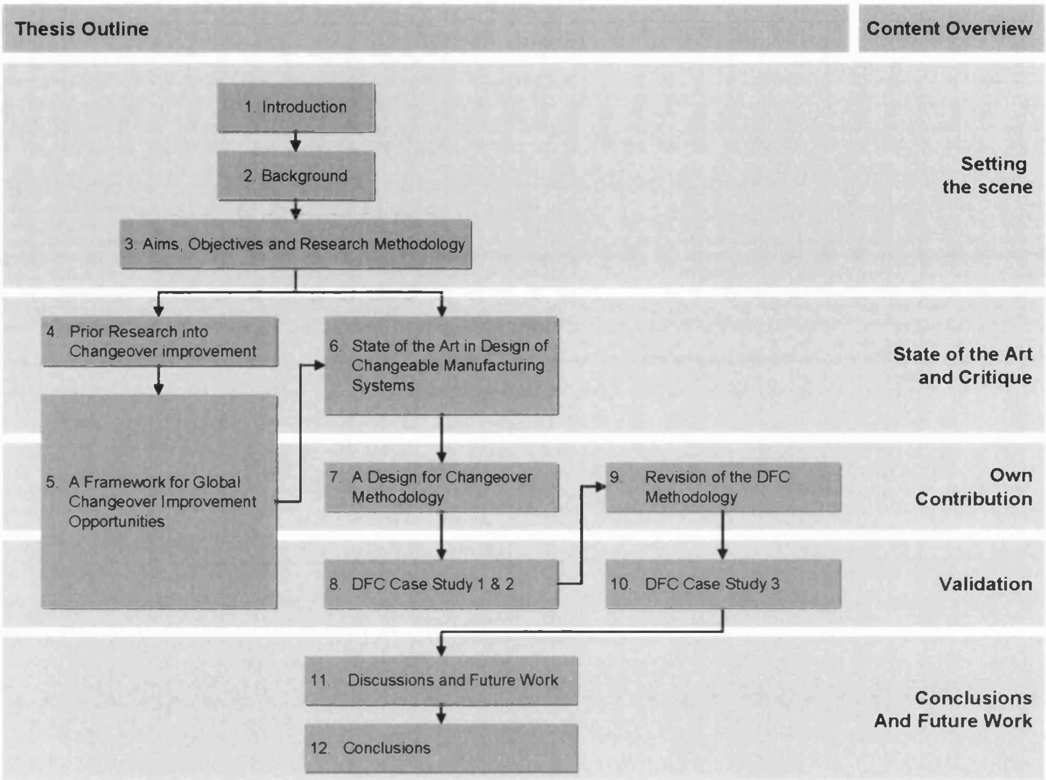

Figure 1.1 Structure of thesis

The outline of this thesis is as follows:

Chapter 2 sets the scene for this thesis with a more detailed introduction to some of the issues modern manufacturing companies are facing. The chapter gives a brief overview on modern manufacturing paradigms aimed at providing manufacturers with the ability to constantly adapt to changing market conditions. The underlying needs for these are subsequently discussed in the light of the emerging paradigm of changeable manufacturing systems. The chapter goes on to define the need for a good changeover capability of manufacturing equipment within the wider need for "changeability" in a manufacturing enterprise.

Chapter 3 defines the detailed aims and objectives developed from the hypotheses identified in Chapter 1. The chapter also briefly reviews different research methodologies and describes the research methodology used in this thesis.

Chapter 4 reviews relevant literature on the subject of changeover improvement. Different approaches widely used in industry and academia are described. Extensive work which has previously been carried out by the University of Bath on this subject is also reviewed.

Chapter 5 analyses the previous chapter's review of prior work on changeover improvement and develops a framework for global changeover improvement opportunities and where they can be found. A selection of small case studies is presented to show the importance of an improvement programme which is balanced between the framework's key areas.

Chapter 6 reviews and discusses related design methodologies for changeable manufacturing systems as described in Chapter 2. Gaps within these are assessed and the requirements for a generic design for changeover methodology are defined. Finally, the issues that the DFC methodology presented in this thesis shall cover are discussed. This includes a discussion of DFC within the framework of global changeover improvement opportunities and the definition of those gaps addressed by the current thesis.

Chapter 7 describes the development of a formal Design for Changeover (DFC) methodology. The chapter presents some basic concepts for modelling and evaluating changeovers. Finally a formal DFC methodology in 9 steps is presented.

Chapter 8 presents two case studies utilising the proposed DFC methodology. The studies show the application of individual steps within the methodology. Areas for improvement of the methodology are discussed.

Chapter 9 revisits the development of the DFC methodology of Chapter 7 and revises it addressing some of the improvements required from the previous case study.

Chapter 10 presents a further extensive industrial case study illustrating the use of the revised DFC methodology.

Chapter 11 discusses the proposed methodology and its validation and outlines areas for future work which have been identified in this thesis.

Chapter 12 reviews the characteristics of the proposed methodology and draws final conclusions.

2 Background

The aim of this chapter is to provide the reader with a more detailed introduction to some of the issues modern manufacturing companies are facing. A brief overview is given on modern manufacturing paradigms which have been proposed to provide manufacturers with the ability to constantly adapt to changing market conditions or change drivers. The underlying needs for these are discussed in the light of the emerging paradigm of changeable manufacturing enterprises. The chapter goes on to position changeover capability of manufacturing equipment as part of this wider view of 'changeability'. The chapter concludes with the definition of the broad scope of the Design for Changeover methodology developed later in this thesis.

2.1 Change Drivers – forces of change for manufacturing systems

The mass manufacturing paradigm is nowadays less applicable to the modern, customer-driven manufacturing environment (Womack *et al.*, 1990, Reik *et al.*, 2005b). Companies increasingly seek to improve their capabilities to react to uncertainties. Due to increasing customer demand for product variety, uncertainties influence today's manufacturing environment more than ever. Thus *Flexibility*, *responsiveness*, *agility, changeability* and *reconfigurability* are watchwords in modern manufacturing (Slack, 1990, Womack *et al.*, 1990, Schuh *et al.*, 2004, Kidd, 1995). The underlying principle is that the better a manufacturing organisation and its associated manufacturing processes and systems can respond to a changing environment the more successful it will be (Reik *et al.*, 2006).

As Wiendahl states:

> *"Changeability has become a decisive factor in the competitiveness of manufacturing companies in addition to the classical target factors of cost, time and quality" (Wiendahl and Heger, 2003).*

Manufacturers are typically faced with changes due to changing customer demands, environmental uncertainties, product variation and variability of processes (De Toni and Tonchina, 1998). These large and very influential driving forces that dictate changes for manufacturing systems are often called *change drivers* (Neuhausen, 2001, Schuh *et al.*, 2004), a term which the author will henceforth adopt.

Wiendahl and Heger (Wiendahl and Heger, 2003) differentiate between direct and indirect change drivers as illustrated in Figure 2.1. In their view the problems manufacturers face are indirectly forced on to them by short-cycled and erratic changes in the environment, society and politics, world economy, and available research and technology.

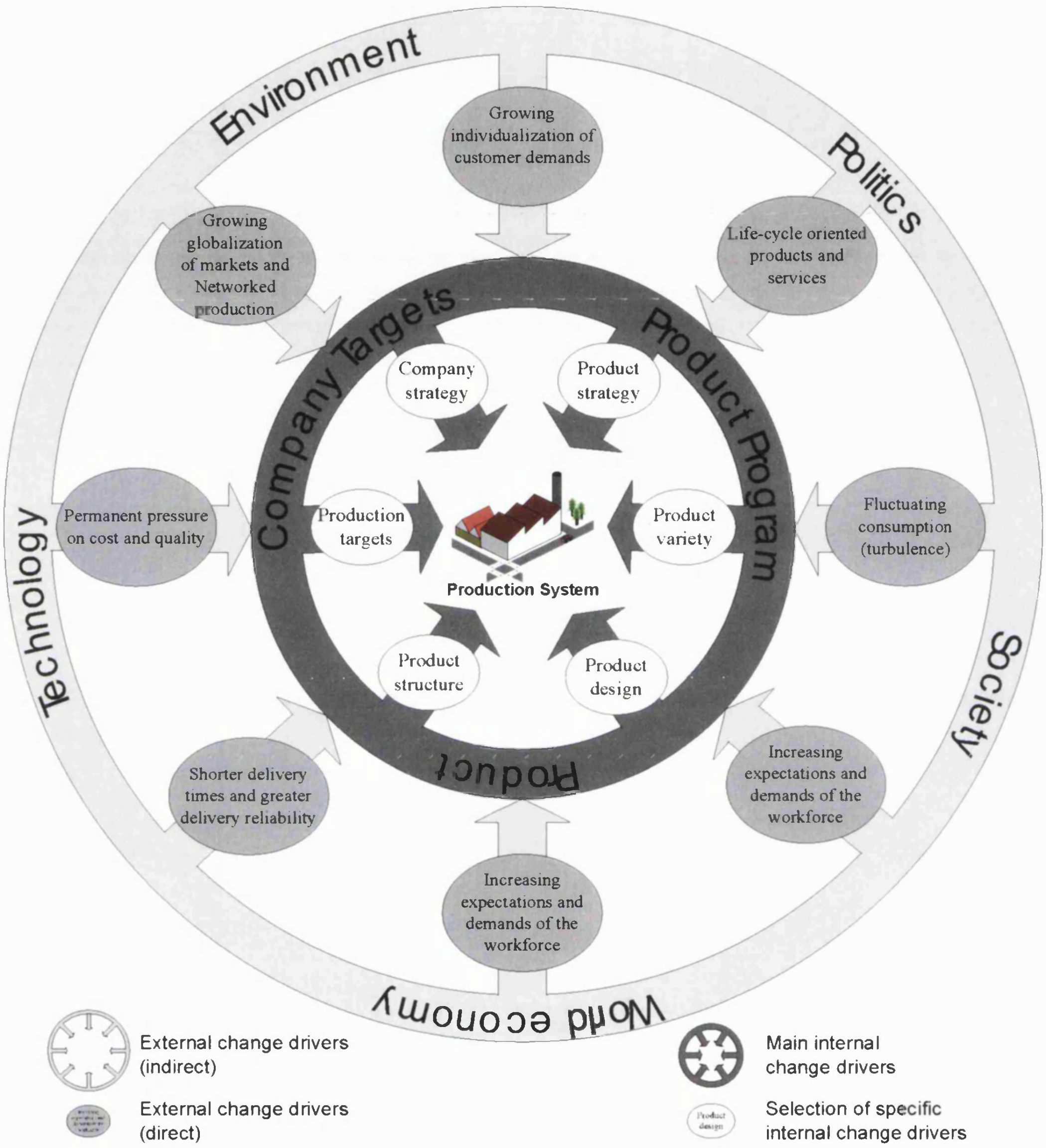

Figure 2.1 Classification of Change Drivers ((Wiendahl and Heger, 2003, Neuhausen, 2001)

Society and politics determine standards and taxation, but also have influence on personnel qualifications and working practices. Research and technology can change the technologies and materials available for manufacturing processes. World economy and markets have an impact on the design of the manufacturing system through the price level, the competition and the market share on the supply and sales markets (Neuhausen, 2001).

These indirect drivers in turn influence what Wiendahl and Heger (2003) identified as direct change drivers which in turn have a direct effect on manufacturing companies.

Neuhausen (2001) distinguishes, in his work on a design methodology for modular assembly systems, between external and internal change drivers (also shown in Figure 2.1). External and internal drivers have an influence on the design and layout of manufacturing enterprises, from a single workstation to global manufacturing networks combining several manufacturing sites and companies. Interestingly, Neuhausen's external change drivers are equivalent to the indirect change drivers of Wiendahl and Heger (2003).

Internal change drivers are changes in company targets, the product program or the product itself. Internal company targets can affect manufacturing systems design through different strategies or production targets. Arguably, a company strategy focused on short-term profit would not invest in technology with a long-term benefit. Equally, the choice between decentralized or centralized manufacturing has a strong influence on the production system.

The product programme defines the necessary capacity requirements for the production system, whereas the product design and structure are the basis for the design of the production system and its structure.

2.2 Modern Manufacturing Paradigms

In the last decades the uncertainties that manufacturers have faced have become more and more apparent to industry and academia. With increased understanding of the impact of a constantly changing environment on profitability, new approaches and techniques are being sought to effectively react to these uncertainties. Changing market conditions increasingly force manufacturers to change the way they operate. Various different manufacturing paradigms and philosophies have emerged over the last decades to help companies to deal with these change processes and these are discussed below; arguably the differences between the various approaches can be quite subtle.

Flexible Manufacturing (Slack, 1990, Goldhar and Jelinek, 1985): The aim of flexible manufacturing is a production system with the flexibility to change the mix, volume and timing of its output. Within this approach, flexibility has the two dimensions, *range* and *response*. The *range flexibility* is the range of states a manufacturing system can adopt in terms of number of different products and output levels. Secondly, the *response flexibility* describes the ease with which a system can be adapted from one state to another. This response flexibility must be considered in terms of time, cost and organisational disruption.

Responsive Manufacturing (Matson and McFarlane, 1998): Responsiveness describes how a manufacturing system or process reacts on disturbances in its environment. Matson and McFarlane (1998) classify disturbances into either Upstream, Internal or Downstream disturbances. Upstream disturbances are disturbances introduced by suppliers or supplied material, e.g. materials quality problems and property variations, supplier production problems and delivery delays. Internal disturbances include information, control and decision-making, production equipment and labour, and material handling and flow. Downstream disturbances are based on the customer or the market through for example changes to orders, demand variation or forecasting errors.

Lean Manufacturing: Lean Manufacturing has effectively been brought to the West by Schonberger (1982) and Hall (1983). The term 'lean' was formed by Womack *et al.* (1990) to describe the paradigms main aim, the reduction of waste throughout a company's value stream. However, for some lean promoters it is not just a set of tools for the reduction of waste (Bicheno, 2003), but a way of thinking which puts the customer first. Once this way of thinking is adopted, lean tools are available to reduce waste to improve benefits for the customer (Bicheno, 2003).

Reconfigurable Manufacturing: Shorter product life-cycles and greater product variety demand that manufacturers find new ways to maximise their equipment's cost effectiveness (Urbani *et al.*, 2003, Wiendahl and Heger, 2003). Modular approaches to system design not only enable flexible processes but also provide manufacturers the ability to change processes by rearranging modules of the manufacturing system (Schuh *et al.*, 2004). Since reuse of expensive manufacturing equipment is enhanced, the cost effectiveness of manufacturing hardware is increased substantially.

Agile Manufacturing: Flexibility and Responsiveness are an important part of Agile Manufacturing (Gould, 1997). However, the concept of agility comprises more than purely reacting quickly to environmental changes (Venables, 2005). The two main factors of Agility are responding to changes and exploiting changes (Dove, 1996, Kidd, 1995). Zang and Sharifi (2001) describe how Agility Capabilities are means to respond to certain "environmental" changes to the business. They are developed by applying Agility Providers, which are tools and methods with which a higher agility can be obtained. Beyond the flexibility which is needed for lean manufacturing, agile manufacturing requires reconfigurable manufacturing systems in order to provide the necessary agility capabilities to react to unforeseen changes from the business environment (Gould, 1997).

Mass Customisation and Personalisation: Mass customisation is a strategy which seeks to enable businesses to exploit market trends for greater product variety and individualisation (McCarthy, 2004). Mass customisation is one way to achieve Product Personalisation (Montreuil and Poulin, 2005). Product Personalisation is a more general concept, which has personalised products or personalised services around these products as its goal (Montreuil and Poulin, 2005). Montreuil and Poulin (2005) identify 5 different types of Personalisation a company can adopt, namely *popularising*, *varietising*, *accessorising*, *parametering* and *tailoring*. Where popularising is based on personalised services around a few standard products, the other types offer increasing variety and customer involvement in product specification. Tailoring is the type with the most customer involvement where the customer supplies the manufacturer with the product specification. This can be, at the top level, engineering drawings to which the manufacturer produces the product or it can be a functional specification when engineering-to-order is required by the manufacturer. Mass Customisation and Personalisation are a response to the micro-segmentation of markets and require that changed practices for manufacturing and marketing processes are introduced across the whole of the supply chain (Coronado *et al.*, 2004).

2.3 Changeability in the Production System

The previous section has given a brief overview of modern manufacturing paradigms. Although these address different aspects, they all aim to increase a company's ability to adapt to changes in some or all of the change drivers identified above (see Figure 2.1). In other words they aim to increase the changeability of a manufacturing enterprise or parts thereof. This changeability can be seen to affect different levels of a company, from the complete enterprise and network of manufacturing locations to a single processing unit or workstation. Overall five distinct levels of a production system have been identified by a number of authors (Zhao *et al.*, 1999, Neuhausen, 2001, Wiendahl and Heger, 2003, Nyhuis *et al.*, 2006). The author's amalgamation and interpretation of these levels is listed below:

1. the production network and enterprise level,
2. the factory, facility and site level,
3. the sub-factory, manufacturing or logistics area level,
4. the manufacturing system or group of workstations level and
5. the processing unit or single workstation level

If a company wants to be able to react to changes initiated by the drivers described in the previous section (see Figure 2.1), sufficient "changeability" is required to be available within all these different levels. Arguably the changeability of one level is influenced by the changeability of its subordinate level(s). Thus, all levels require to be specified and designed in a changeable manner.

Wiendahl *et al.* (Wiendahl and Heger, 2003) and Nyhuis *et al.* (Nyhuis *et al.*, 2006) combine these different levels of a company with a classification for the product or product portfolio:

1. Product portfolio
2. Products
3. Sub-products
4. Part
5. Feature

The combination of these two classifications allows Nyhuis *et al.* (Nyhuis *et al.*, 2006) to identify five different types of changeability which are illustrated in Figure 2.2:

Changeoverability describes the technical ability of a processing unit to perform particular operations on a feature of a part or assembly at any desired moment with minimal effort and delay.

Reconfigurability describes the practical ability of a manufacturing system to switch reactively and with minimal effort and delay to a particular number of parts through the addition or removal of single functional elements within the system.

Flexibility refers to the tactical ability of an entire sub-factory, to switch reactively and with reasonably little time and effort to new – though – similar families or sub-products by changing manufacturing processes, material flows and logistical functions.

Transformability describes the tactical ability of an entire factory or site to switch reactively or proactively to other products.

Agility stands for the strategic ability of an entire enterprise – mainly proactively – to open up new markets, to develop the requisite product and service portfolios, and to build up the necessary production capacity.

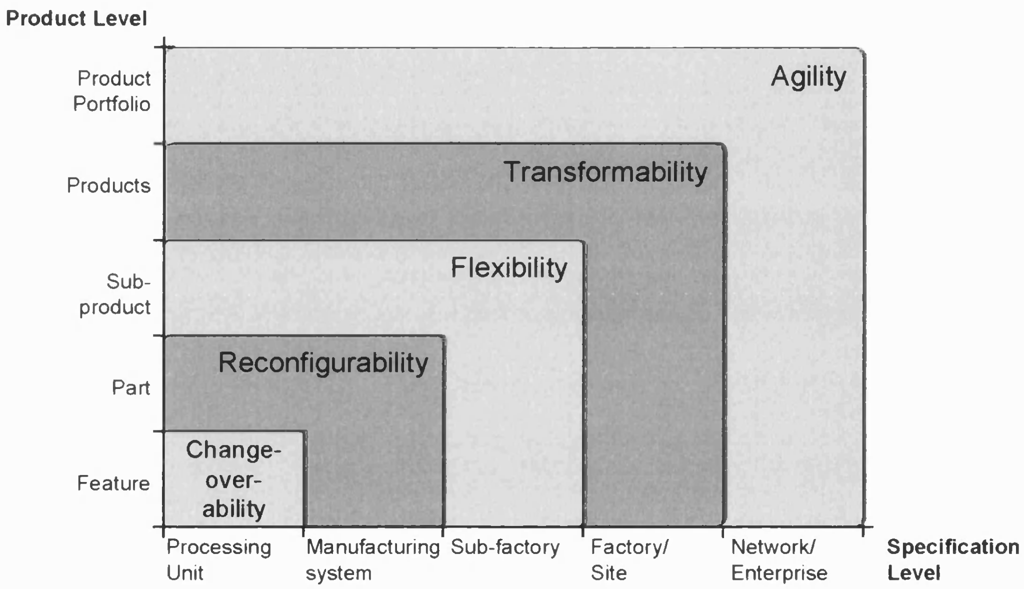

Figure 2.2 Types of Changeability (from Nyhuis *et al.* (Nyhuis *et al.*, 2006) and Wiendahl *and Heger.* (Wiendahl and Heger, 2003))

The higher levels of changeability build upon the lower levels. Thus, agility of an enterprise and its product portfolio is only possible if changeability is sufficient in all the subordinate levels of the enterprise and the product.

The base element changeoverability is the technical capability of manufacturing equipment to carry out manufacturing processes on features of parts and assemblies. This can be seen as the core of changeability which is required for all other forms of changeability to be successful.

2.4 Conclusions

This chapter has given an overview of the field of changeable manufacturing systems and has defined changeoverability from this point of view. A brief overview was given of modern manufacturing paradigms, which share the fundamental aim to enhance the ability of manufacturing systems and enterprises to react quickly to changes in the market. The chapter has also discussed the underlying forces, i.e. the change drivers, behind the uncertainties manufacturers are facing at present. As has been shown it is now widely believed by academics and industrialists that to be able to react to these change drivers changeability is essential. This need for changeability on different levels of the manufacturing enterprise has been discussed. It has been shown that changeoverability is "the technical ability of a processing unit to perform particular operations on a feature of a part or assembly at any desired moment with minimal effort and delay" (Nyhuis *et al.*, 2006) and is as such a core characteristic of changeable manufacturing systems.

The aim of the work presented in this thesis is to provide equipment designer with structured guidance in order to design manufacturing equipment with good changeoverability from the outset. The following chapter will discuss the detailed aim and objectives and describe the applied research methodology.

3 Aims, Objectives and Methodology

The aim of this chapter is to describe the methodology behind the research presented in this thesis. The chapter begins with the definition of the aims of the research and the identification of detailed objectives. Following this a brief review of research methodologies is given and the research approach used is described.

3.1 Aims and Objectives

There are two overall aims of the research which reflects the two strands of this thesis as outlined in chapter 1. The overall aims are:

Aim 1: To develop a framework for global changeover improvement opportunities

Aim 2: To formulate design guidance for equipment designers in a generic Design for Changeover (DFC) methodology

Detailed objectives can be deduced from these aims. The following objectives have been defined for the *Aim 1*:

- To analyse changeover improvement opportunities identified within literature based case studies
- To codify or classify different types of improvement opportunities
- To develop a framework which encompasses all global improvement opportunities
- To validate and qualify this framework with industry case studies

To achieve *Aim 2* the following objectives have been deduced:

- To codify and quantify the design elements that constitute and facilitate changeovers in a variety of areas and a variety of industrial domains
- To develop a formal Design for Changeover (DFC) methodology for equipment design which can be applied during the new equipment development process, but also for retrospective improvement initiatives
- To derive, validate and qualify the developed methodologies in a variety of industrial environments

3.2 Research Methodology

Hornby states that research is the careful study of a subject, especially in order to discover new facts or information about it (Hornby, 2000). Many different research approaches have been proposed in the literature. Howard and Peters (Howard and Peter, 1990) for example have categorised different research methods in management research into pure basic, basic objective, evaluative, applied and action research. These describe different ways in which knowledge can be gained through observations, data collection and theoretical considerations. From a more general point of view these approaches can be categorised depending on how they relate the concepts of research and theory. These concepts and their relationships in different methodologies are discussed in the next sections.

3.2.1 Research and Theory

In regards of the relations between research and theory there are two main approaches to research, namely deduction and induction (Bryman, 2004). These two types of research are distinctive as they describe opposite relationships between theory and research. The deductive approach starts with theoretical considerations of a particular domain in which observations and findings are carried out to confirm or reject hypotheses. An alternative approach to deduction is induction where theory is the outcome rather than the starting point of the research process. A theory is then the inference of generalisation of observations made through the research. The deductive and inductive research approach and their relations between theory and research are illustrated in Figure 3.1.

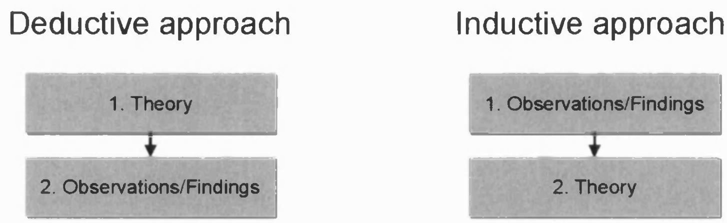

Figure 3.1 Deductive and inductive approach to the relationship between theory and research (Bryman, 2004)

3.2.2 Research Methods

Although some researchers prefer an inductive stance, most research is carried out in a deductive manner. In this case the research process consists of six distinctive steps as illustrated in Figure 3.2.

The deductive approach is based on the deduction of one or more hypotheses based on the theoretical considerations of a particular domain. These hypotheses are then being empirically scrutinised through gathering data and establishing findings. The way data is collected to provide useful results in relation to the hypotheses is defined by the prior translation of hypothesis into researchable entities (Bryman, 2004).

The deductive research process often concludes with an inductive step when gained knowledge through findings and confirmed or rejected hypotheses is fed back to the domain of enquiry and result in an updated theory.

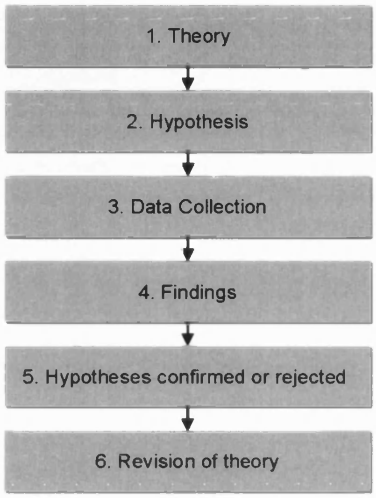

Figure 3.2 The deductive research process (Bryman, 2004)

It is noted that although the deductive approach is depicted as a linear process, in reality this is often not followed strictly. Also, often research is iterative where the researcher is going back and forth between data and theory stages of the processes (Bryman, 2004).

Rose (Rose, 1982) proposes a model which shows how the key components of research are related. The relations between individual components are given by linking theory and evidence (Trafford, 2001). The research method Rose uses in his model consists of 5 steps, but in principle is very similar to Bryman's deductive research process:

1. Theory
2. Theoretical propositions
3. Operationalisation
4. Field work

5. Results

Trafford extends Rose's model by showing three different types of validity, namely internal empirical, internal theoretical and external validity. This is illustrated in Figure 3.3.

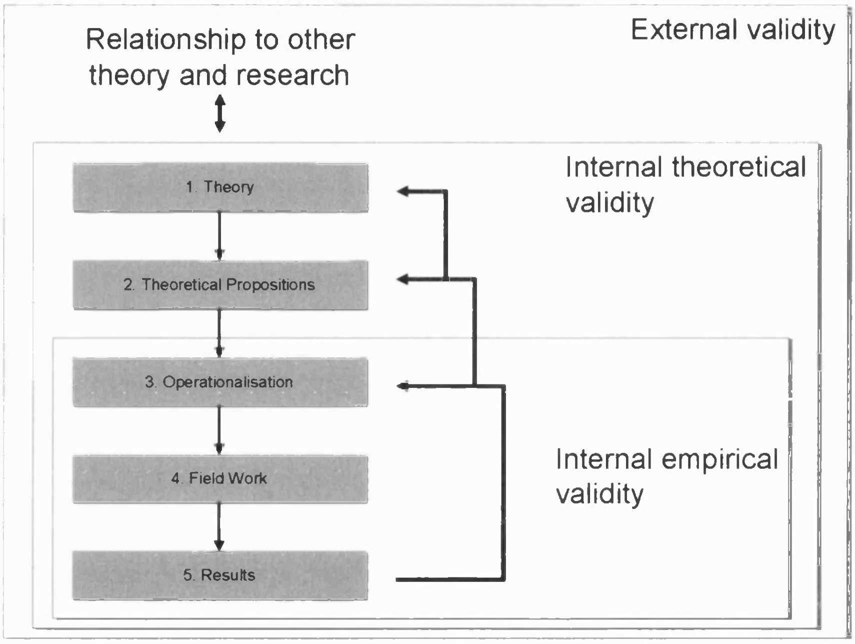

Figure 3.3 Rose's research model and distinction between three kinds of validity in research (Trafford, 2001)

3.2.3 Research approach in this thesis

The research technique applied for this work is a literature and case study based assessment of current practice to identify the extent and impact of design-led changeover improvement opportunities. In addition, action research techniques are employed as data collection mechanism during projects with industrial collaborators. The research was informed by visits, workshop participation, training sessions or more detailed collaboration projects with over 20 different companies.

Overall a combination of Bryman's (Bryman, 2004) and Rose's (Rose, 1982) research approaches is used. The different stages of the research presented here and where they are described in this thesis is depicted in Figure 3.4.

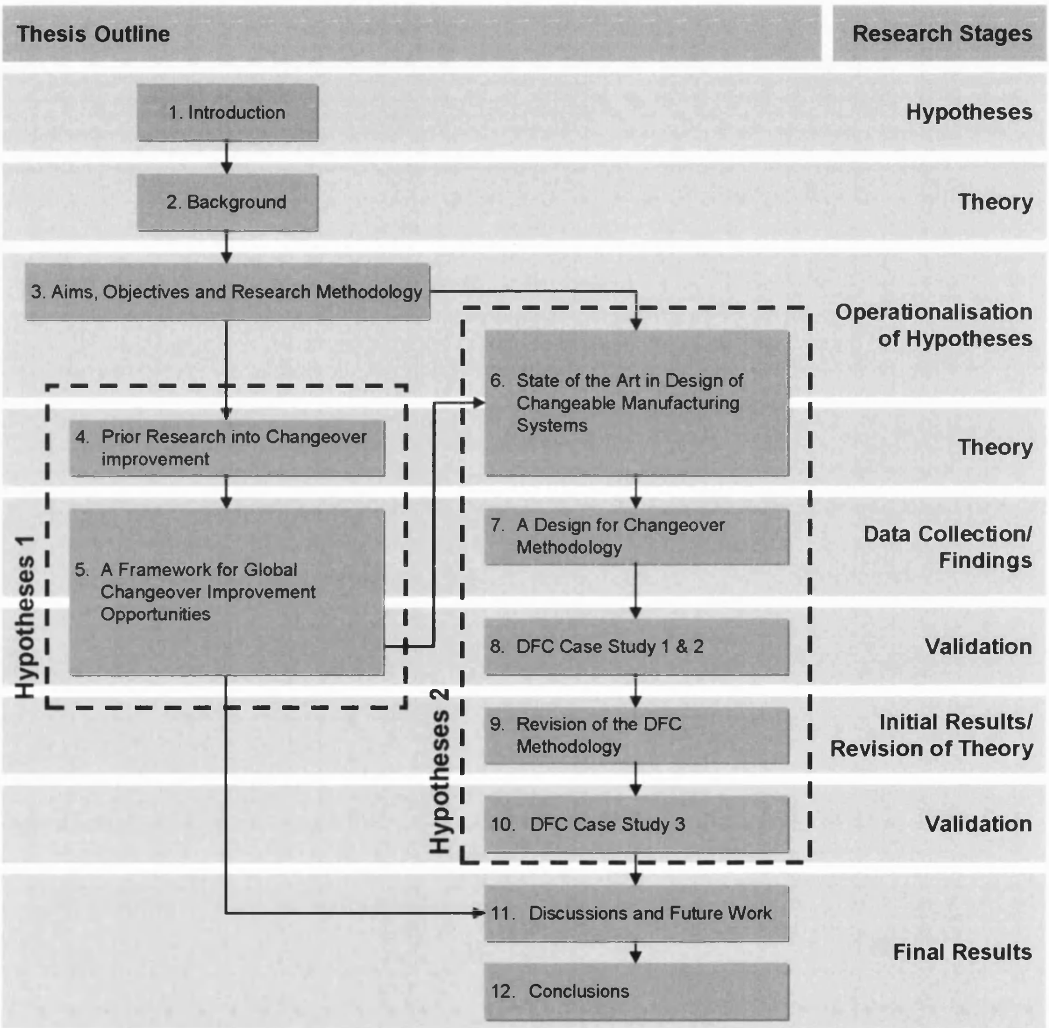

Figure 3.4 Stages of research method and the chapters where these are described

Figure 3.4 also illustrates the two strands of the thesis, which each address one of the hypotheses defined in Chapter 1. The hypotheses underlying the two research strands in this thesis are here restated as research questions:

- *Research Question 1:* Can a framework be developed which classifies global changeover performance improvement ideas and also clearly depicts the difference between organisational-led and design-led improvement ideas?
- *Research Question 2:* How can design guidance for equipment designer be formulated as a generic Design for Changeover (DFC) methodology?

Chapters 4-6 address the first research question; Chapters 7-11 address the second research question. Results and conclusions of both research strands and future work are discussed in the final chapters 12 and 13.

As part of the validation process of the developed methods results of the research have been published in four conference papers and two peer reviewed journal papers. One of the conference papers was selected for the publication as chapter in a best paper book edited by the conference organisers (Reik *et al.*, 2006). Also, the work has been presented to a wider academic and industrial audience in a number of Design for Changeover (DFC) Workshops within companies and at the University of Bath. The DFC methodology has also been on display on several national and international trade shows.

4 Prior Research into Changeover Improvement

Considerable attention has been given to the subject of changeover improvement since the limitations of the mass manufacturing paradigm have become understood (Shingo, 1985, Womack et al., 1990). Today there is a trend to complete ever greater numbers of changeovers on manufacturing equipment (Schonberger and Knod, 1997). With pressure to enact small batch multi-product manufacture the need for both high quality and rapid changeovers is readily apparent if poor line utilisation and deficient product quality are to be avoided (Bicheno, 2003, McIntosh et al., 2001, Suzaki, 1987). This chapter first reviews various definitions of changeovers within the literature and continues with a description of different areas where benefits of improved changeover performance can be sought. Finally, the chapter reviews approaches with which improved changeover performance can be achieved.

4.1 Changeover definition

The changeover process is often only defined in terms of time elapsed from last good part to first good part (Trevino et al., 1993). McIntosh *et al.* (2001) define changeover time as the time elapsed from the point when full production of product A ceases to the point where manufacture of product B has reached set output and quality rates. Figure 2 illustrates that a changeover potentially includes three distinguishable phases: run-down and run-up phases as well as the always present set-up phase during which the line is static (McIntosh *et al.*, 2000). There are important implications when including these three phases in the definition. The most notable implication is that markedly differing activities can arise during the successive phases. Also, the run-down and run-up phases together potentially contribute significantly to the overall changeover duration and losses (Mileham et al., 2004). While seeking changeover improvement, it is important that all of these activities – across the changeover as a whole – are considered. This also applies to a fully comprehensive DFC methodology.

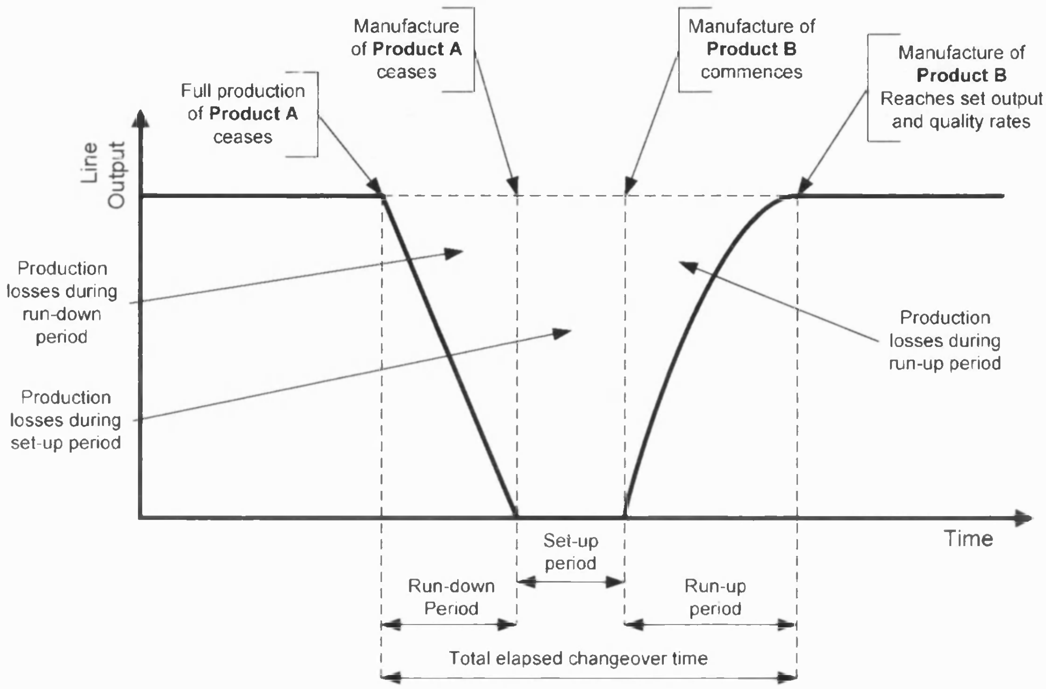

Figure 4.1 Representative line output during a changeover

Research has also established that activity during the set-up phase is very influential upon what occurs during the run-up phase (Smith, 1991, Sladky, 2001). Thus, it may be possible that seeking to minimise set-up duration might jeopardise run-up performance and so prejudice the total changeover loss. Thus, a more holistic view is necessary, seeking time reduction across the changeover as a whole and giving attention to the quality to which settings are made.

4.2 Benefits of Improved Changeover Performance

Benefits arising from improved changeover performance are likely to occur in many areas throughout a business. McIntosh *et al.* (McIntosh et al., 2001) classify these benefits into 5 high-level categories as shown in Figure 4.2.

Categories	Benefits
Reduced Equipment Downtime	1.Greater line volume 2.Integrated Maintenance
Reduced Inventory	1.Lower finished goods inventory 2.Lower work-in-progress
Reduced Resources	1.Lessened manpower requirement 2.Lower changeover skill requirement 3.Equipment updating 4.Space release
Enhanced Flexibility	1.Better response to market needs 2.Better accommodation of internal uncertainty 3.Better potential to supply niche markets 4.Better potential for taking high-margin business
Enhanced Process Control	1.Enhanced Process quality 2.Increased Process reliability 3.Increased process volume capability 4.Reduced equipment damage 5.Reduced scrap rates 6.Enhanced safety

Figure 4.2 Possible benefits of improved changeover performance (McIntosh et al., 2001)

It is frequently assumed that a greater production volume through reduced downtime is the area where improved changeover performance has the biggest impact (McIntosh et al., 2001). Although this might be true in some cases, care needs to be taken that possible benefits in all areas are considered. Also trade-offs between benefits must be considered. A case study by McIntosh *et al.* (McIntosh et al., 2001) illustrates how potentially much higher benefits can be achieved by utilising time saved through improved changeovers to perform more changeovers in the same time rather than using the time gained to increase line output. Mileham *et al.* (Mileham et al., 1997) describe that the desire for high OEE figures can be misleading. Rather than encouraging businesses to do less time consuming changeovers more frequently in order to reduce inventory and lead times it simply identifies changeover as one of the major losses. As a result it is frequently targeted to reduce the number of changeovers which occur. This reduces the potential commercial benefits that would come with enhance flexibility (see Chapter 2). Newer Total Productive Maintenance (TPM) approaches - sometimes also called Total Productive Manufacture - are dealing with this by measuring OEEs on different levels such as floor-to-floor and door-to-door (Willmott, 2004).

Quantification of possible benefits is not always easy to assess. In particular, those benefits arising within 'Enhanced Process Control'. Therefore they historically provided little justification for improvement initiatives. However, the potential benefits have become increasingly understood throughout academia and industry (Bicheno, 2003, Schloz, 2006). This has partly led to the development of new manufacturing paradigms, the most important of which have been discussed in Chapter 2.

4.3 Existing Methods for Improving Changeover Performance

Many methods for improving changeover have been proposed in the literature. One of the first who recognised the benefit of shorter changeovers was Shingo (Shingo, 1985). His Single Minute Exchange of Die (SMED) method is widely known today and 'SMED' is often used as a synonym for changeover improvement and set-up reduction. The SMED methodology comprises of four stages (Shingo, 1985):

- Preliminary Stage – Internal and External Setup Conditions are not distinguished
- Stage 1 – Separating Internal and External Setup
- Stage 2 – Converting Internal and External Setup

- Stage 3 – Streamlining all aspects of the Setup operation

Shingo (Shingo, 1985) describes different improvement techniques which he assigns to these four stages as illustrated in Figure 4.3.

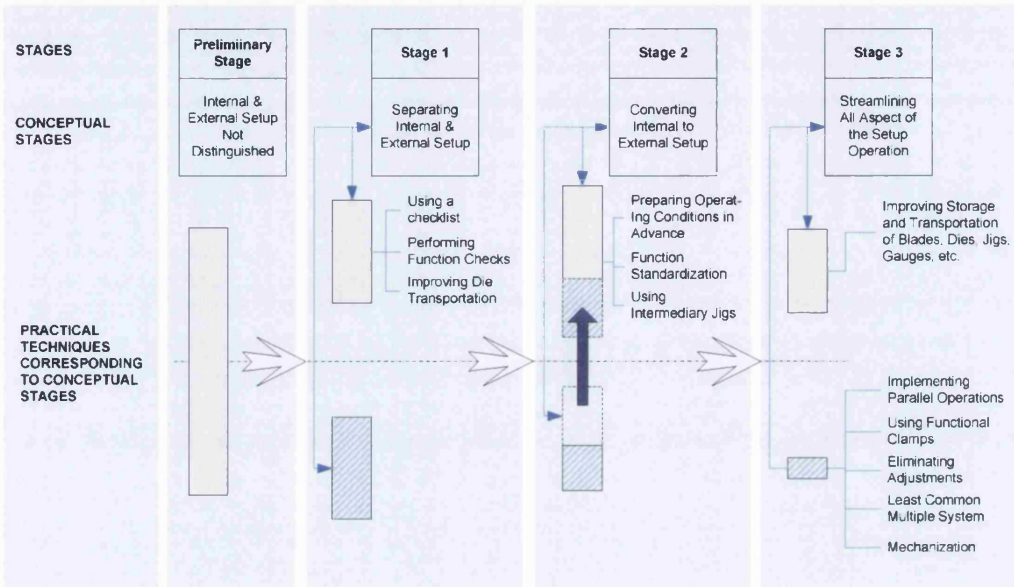

Figure 4.3 The Single Minute Setup (SMED): Conceptual Stages and Practical Techniques (Shingo, 1985)

Similar approaches to SMED have been proposed in (Claunch, 1996, Zunker, 1991, McIntosh et al., 2001). Also Sekine *et al.* (Sekine and Arai, 1992) advocate kaizen for quick changeover as a target driven method to reduce changeover waste. They define three types of changeover waste, namely setup waste, replacement waste and adjustment waste.

Gest (Gest, 1995) proposes a so called 'Reduction-In' method to improve changeover performance. The 'Reduction In' method is basically a classification scheme for set-up reduction techniques. The system is based on the classification of changeover problem areas into four categories, namely excess effort, excess variety, excess adjustment and excess online activity. Gest describes these four excesses as follows:

- **Online activity** – Work carried out while machine is out of production
- **Adjustment** – Too much setting to achieve exact positions or settings
- **Variety** (Parts, tooling and machines) – Lack of standardisation
- **Effort** – Too much physical work

Gest suggests that once these excesses have been identified, improvement opportunities can be sought which reduce or eliminate these excesses. Figure 4.4 illustrates how Gest classifies various set-up reduction techniques to his 'Reduction-In' method. The figure also indicates a suggested order of implementation, possible impact of the set-up reduction techniques and associated costs. Through the classification, Gest is claiming to have developed a link between 'what needs to be improved' (problematic changeover activity) and 'how it can be improved' (changeover improvement techniques).

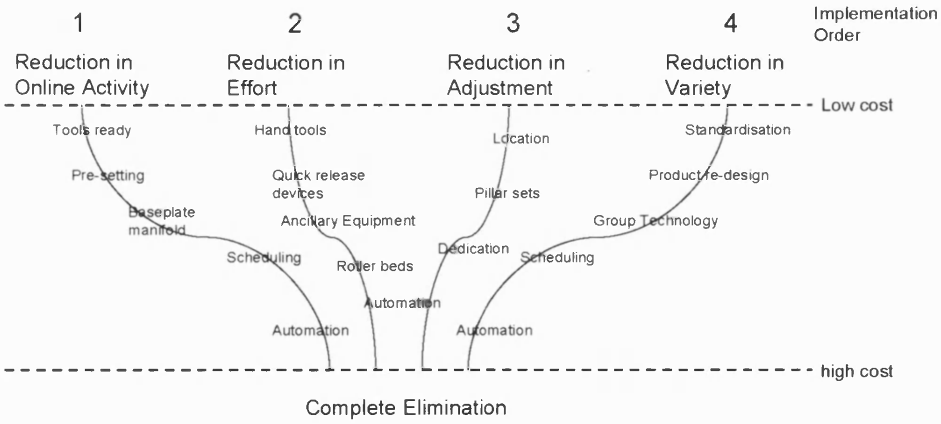

Figure 4.4 Functional Classification Schema for Set-up Reduction Techniques within the Reduction-In System (Gest, 1995)

McIntosh *et al.* *(McIntosh et al., 2001)* have developed the concept of the organisation-design spectrum to show that improvement most likely incorporates elements of both, design and organisational change. McIntosh *et al.* (McIntosh et al., 2000) argue that Shingo's SMED method and other similar approaches to changeover improvement favour operational-led improvement efforts.. Although some of Shingo's practical techniques suggest design changes, most of them are organisationally biased. This bias of SMED-based changeover improvement efforts, they argue, is strengthened by the natural desire for quick-fix and low-cost improvements in a retrospective improvement environment. This can cause many improvement opportunities not being considered, because they require capital expenditure. Care has to be taken when dismissing improvement opportunities as to consider potentially hidden costs, such as sustainability of improvements and the quality of changeovers (Culley et al., 2003).

Sekine and Arai (1992) recognise the importance of design-led improvement and support it with case studies. Similar to Shingo (1985) they also provide some design rules. However, these are mostly very specific and often aimed at the improvement of die exchange and changeover of related equipment such as presses and feeding devices. No generic design guidance is provided. This is also true for a larger set of design for changeover rules which have been compiled by Mileham *et al.* (Mileham et al., 1999) and have subsequently been expanded by Van Goubergen *et al.* (Van Goubergen and Van Landeghem, 2002). These design rules are shown in Table 4.1.

Zepf UK (ZEPF, 2006), a leading supplier of change parts for bottle handling and filling lines, employs the so-called 3T philosophy, "No Time, No Tools, No Talent" (Robinson, 2005). This is the underlying concept behind their continuous efforts into improving changeover performance on bottle filling lines. Zepf UK's change parts make excessive use of special fastening and clamping device to make tools unnecessary. The ease of use of these devices combined with a clear colour-coding scheme of the light-weight change parts allows changeovers to be performed by the line operators instead of specialist changeover personnel (Woodrow, n/a, Accessed 14 April 2005). This eliminates the need for specially trained and experienced changeover personnel.

Table 4.1 Design for Changeover Rules from (Mileham et al., 1999) and expanded by (Van Goubergen and Van Landeghem, 2002))

1. Less weight

1.1 Use lighter materials
1.2 Use less material

2. Simplification

2.1 Reduce number of mechanisms
2.2 Eliminate the need to remove non changeover parts
2.3 Eliminate the need to remove complete assemblies
2.3 Remove complete assemblies/modules that can be prepared off-line instead of removing and mounting several smaller parts on-line
2.4 Eliminate pipe connections or use quick release couplings
2.5 Reduce the number of hand/power tools required
2.6 Reduce the total number of components in a tool
2.7 Simplify control procedures such as timing diagrams
2.8 Use short power drive connections
2.9 Use Poka Yoke systems (mistake-proof systems)
2.10 If a part that needs to be exchanged has only 2 sizes, put one fixed on the machine

3. Standardisation

3.1 Use the same size shut heights for presses
3.2 Use the same size securing bolts
3.3 Use the same type of electrical motors
3.4 Design universal machine parts that do not need to be exchanged

4. Securing

4.1 Use the minimum number of fasteners consistent with strength
4.2 Eliminate manually operated clamps
4.2 Use manual clamps as a cheap and fast alternative for bolts and screws
4.3 Use 1/4 turn devices
4.4 Use quick fixtures
4.5 Use hydraulic, pneumatic or electromagnetic fixtures

5. Location and adjustment

5.1 Eliminate on-machine adjustments
5.2 Provide intelligent adjustment and monitoring
5.3 Eliminate the use of spacers and shims
5.4 Provide dead stop positioning
5.5 Provide positioning using centring pins/holes
5.6 Use discrete positioning of parts instead of continuous
5.7 Settings 'right from the first time'
5.7.1 Identify all parameters that influence the process
5.7.2 Determine the correct setting values for all parameters, per type of product – these values need to be written in the set-up instruction
5.7.3 Install means to effectively set these values
5.8 Enable off-line checking of products by improving the quality of setting activities
5.9 Provide measuring devices, preferably using digital displays
5.10 Use stepping motors for accurate setting
5.11 Every knob/wheel needs to have a measuring scale
5.12 If possible, use 1 setting parameter per product property/specification
5.13 Provide re-adjusting procedures that give a direct link between an observed fault on the product and the parameter that has to be re-adjusted, together with how much it needs to be re-adjusted

6. Handling/Movements

6.1 Eliminate the need for or ensure easy cleaning/purging
6.2 Eliminate the need to handle hot items
6.3 Eliminate the need to handle awkward items
6.4 Provide power aids
6.5 Provide remote actuation
6.6 Ensure easy delivery of tools
6.7 Provide good access
6.8 Appropriate placement of buttons and control panels to avoid additional/unnecessary movements

7. Off-line activities

7.1 Enable off-line mounting/removing of aids, supports and fixtures
7.2 Enable off-line loading of numerical control data for PLC, CNC (before set-up)

8. Machine lines

8.1 Decouple the drive of every station to enable set-up activities on a single station while the last/first products run through the other workstations

4.4 Modelling of changeovers

The previous section introduced various changeover improvement techniques and methods. All these methods comprise an initial changeover analysis phase, where data is gathered about changeover activities and the issues are identified. In order to better understand activities and operations involved in changeovers, several ways to representing and visualising changeovers have previously been developed and used in the literature on changeover improvement. It was considered useful to bring together all of these techniques and show how they complement each other. Table 4.2 compares and contrasts the different changeover improvement approaches in regards to their use of different types of changeover visualisation and changeover analysis techniques.

Table 4.2 has been developed from the analysis of the literature to show that most work previously carried out in the area of changeover improvement has involved some form of task analysis sheets to record changeover operations and multi-activity charts to visualise them.

The task analysis sheets are mostly presented in a tabular form and the details recorded in the different formats which can be found in literature often vary considerably even within the same body of work. However, all task analysis sheets generally comprise the type of changeover[1] recorded, the date it was recorded, the duration of the different changeover operations and some form of description of these operations. Besides a short task description and the duration of the task, the task analysis sheets often also feature columns where tasks can be classified as internal or external activities.

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[1] The type of a changeover is often seen from a product point of view and it describes the differences in the products before and after the changeover. The type of changeover can be described in various depths of detail. Often it is simply a list of product parameters which are affected by the changeover (e.g. height or decoration change), but it can also include the values which those product parameters take for the before and after product (e.g. height change 130ml to 150ml)

Table 4.2 Comparison of different representation techniques for changeover operations used

Re-presenting and Modelling Change-over	Changeover Improvement Approaches					
	SMED (Shingo, 1985)	**Quick Die Change** (Smith, 1991)	**Retrofitting for Quick Die Change** (Zunker, 1991)	**Kaizen** (Sekine and Arai, 1992)	**Gest et al.** (1995)	**McIntosh et al.** (1998 and 2001)
Task analysis sheets and Multi-activity charts	Task analysis sheets and Multi-activity chart	Hit-to-hit analysis sheets (tasks with times)	Setup process, chart, Sequence of operation diagram	Sequence Chart, Operator-Machine Chart of joint operations	Task analysis sheets	Task analysis sheets and Multi-activity charts
Differentiating of Internal and external operations	Yes, basis of one of the fundamental improvement techniques	yes	yes	Yes, basis of one of the fundamental improvement techniques	Yes, basis of one of the fundamental improvement techniques	Yes, basis of one of the fundamental improvement techniques
Definition of change-over activity types	-	-	5 classes (Clamping, Adjustment, Inspect, Get-Find, Other)	-	9 classes (Movement, Adjustment, Securing/Releasing, Problem, Waiting, Inspect, Control, Cleaning, Set-up start/finish)	15 types (Problem, Securing, Adjustment, Location, Trial, Special Skill, Tool employed, Seeking/using data, Movement, Waiting, Interruption, Removal, Multi-person, Access, Clean)
Graphical activity modelling	-	-	-	-	yes	-
Route analysis	Some alternative die routing examples	yes, diagrams for various die routing examples	yes, diagrams for various die routing examples	yes, diagrams for operator and die movement	-	-

What is considered a changeover activity is often not defined in any other way. Only Zunker (Zunker, 1991) and Gest (Gest, 1995) have really attempted to classify the different types of activities which can occur during a changeover (see Table 4.2) and thus tried to model changeover operations carried out by changeover personnel. Zunker and Gest both have additional columns in their changeover analysis sheets to classify operations as one of their different types of activities. Gest (Gest, 1995) also developed a graphical activity modelling language which is based on Gilbreth's motion study (Gilbreth, 1911). Each of the 9 classes of changeover activities is given a separate symbol as illustrated in Figure 4.5.

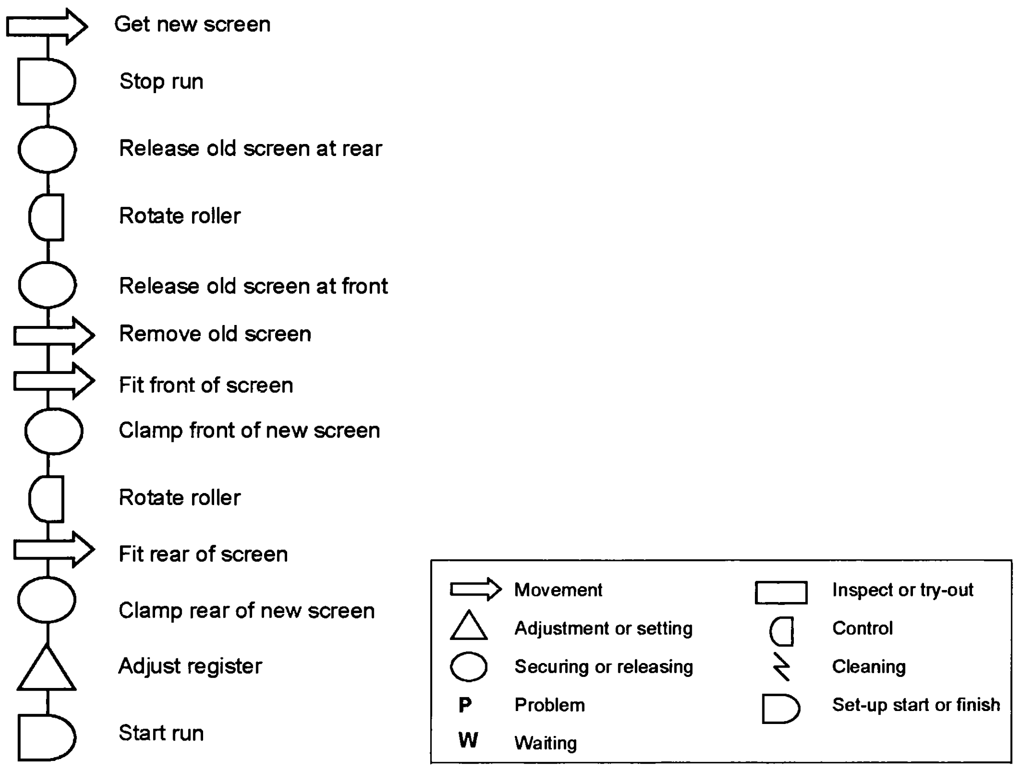

Figure 4.5 Graphical description of a screen printing changeover (Gest, 1995)

McIntosh *et al.* (McIntosh et al., 2001, McIntosh, 1998) use 15 changeover activity types to describe changeover tasks. However, these are not exclusive classes, but rather a set of predefined attributes with which changeover tasks can be described. Some of these types are based on Gest's classification of changeover activities (Gest, 1995). Gest's activity types are describing the actions of the changeover personnel; the additional activity types of McIntosh *et al.* can be used to highlight reasons for extended task duration or to indicate that a task requires additional resources, such as tools, skills, data or additional personnel. As such they are meant to increase the understanding of the individual changeover activities and assist in identifying and prioritising potential improvement opportunities.

McIntosh *et al.* (McIntosh et al., 2001) use a changeover analysis sheet which is split into two sections (see Figure 4.6). The first one describing basic task details, such as task description, time when task was completed and who performed the task. The second section is thought of as an analysis section and it is aimed to assist in increasing the understanding of the changeover tasks and in selecting possible improvement options. Part of this is the activity of associating activity types to each individual task. This, as the authors state, requires more thought and "should be made only after the basic recording exercise" (McIntosh et al., 2001) has been completed.

Changeover Equipment: Recorded by: Document Ref.:		 Date / Time: Changeover Personnel:
Changeover Start Time:	First Piece Manufactured at:	Changeover complete at:
Changeover From/To: (Changeover type)		

Section 1					*Section 2*		
Task ('major')	**Task** ('detail')	**Time Complete**	**Who?**	**Notes**	**Activity Type**	**Duration**	**'Reduction-In' Opportunity**

Figure 4.6 Changeover Audit Sheet from McIntosh et al. (McIntosh et al., 2001)

4.5 Prior work on changeover improvement at the University of Bath

Research on improving changeover performance has been carried out at the University of Bath since the early 1990s. Since then several research, PhD and student projects have been completed on this topic. The work was carried out in close collaboration with companies from various industry sectors. Overall University of Bath researchers have visited and worked with some 100 different plants and companies at different levels of involvement.

Figure 4.7 outlines the research carried out by various academics at the University of Bath. Key research output in terms of publications and PhD research outcomes are also shown. Major publications on the field of changeover improvement include two books (Mileham et al., 1996, McIntosh et al., 2001), a book chapter in a Mass Customisation book (Reik et al., 2006) and 9 peer-reviewed journal papers.

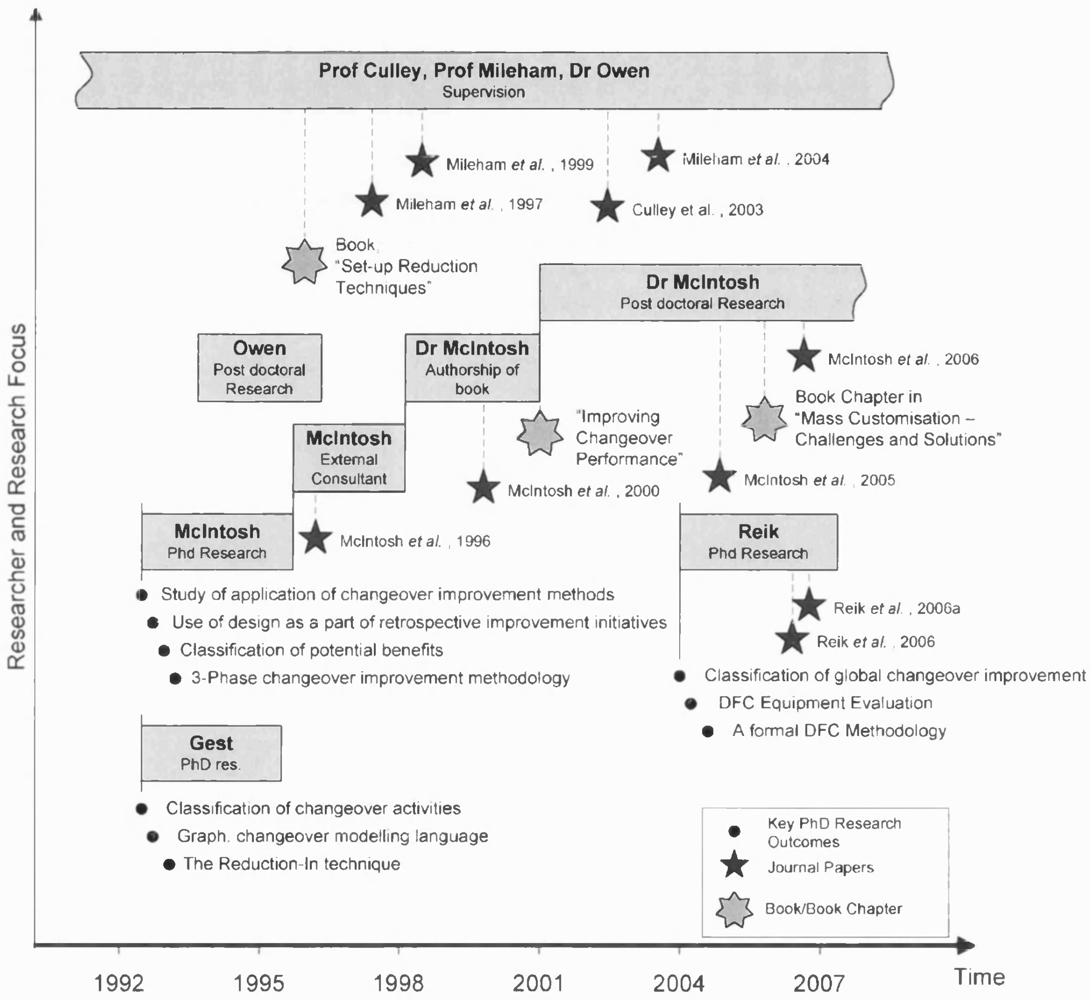

Figure 4.7 Researcher and key research outcomes on improving changeover performance at the University of Bath

The research was also assisted by many final year student and group design and business projects. Topics addressed by student projects in recent years include the application and validation of DFC in different industry environments (Ostle, 2005, Moorhouse, 2006), financial benefit assessments of improved changeover performance (Bado, 2005) and product design for changeover (Chan, 2006). There have also been a number of industrial Knowledge Transfer Partnership (KTP) activities between the University of Bath and industrial collaborators that have focused on changeover improvement and have enabled the approaches to be tested.

4.6 Discussions

Over the past twenty years there has been considerable evidence of the use of Shingo's SMED methodology (Shingo, 1985), which has been the basis of the effort of many organisations to retrospectively improve their process changeover performance (McIntosh, 1998). This approach is also widely supported in both academic and industrial literature (Sekine and Arai, 1992) and receives little criticism. Indeed, given the achievements that have been documented, the methodology's high standing is fully justified (Shingo, 1985).

Yet a number of shortcomings, for example in their book, McIntosh *et al.* (McIntosh et al., 2001) argue that the focus is often heavily concentrated on organisational-led improvement and that the benefits of hardware amendment are often considerably under-exploited. Equally, Culley *et al.* (Culley et al., 2003) provide evidence over a 10 year time frame that SMED programmes can fail to sustain the gains that have been made. Arising from these and other concerns McIntosh *et al.* (McIntosh et al., 2005) have proposed a revised improvement framework to make a full compliment of potential improvement opportunities more accessible to retrospective practitioners.

The hypothesis that there is a bias in retrospective improvement programmes towards organisational refinement has been elaborated upon by Reik *et al.* (Reik et al., 2005b) who present possible improvement opportunities under a framework of People, Practice, Process and Products (A detailed description of this framework will be provided in the following chapter). It is described that the people who are engaged, their motivation, the training they receive and the procedures they adopt all represent opportunities for organisational refinement wherein, typically, the process hardware they work upon remains substantially unaltered. There are benefits of seeking improvement in this way, not least of which is the generally low cost of such programmes and the short time scale needed to gain improvement (McIntosh et al., 2001).

Equally there are also the likely benefits of a greater use of design-based improvement (particularly applicable to both Processes and Products (Fischer et al., 1999)). Notwithstanding changeover time savings, which might be realised by this route (McIntosh et al., 2001, Whitney, 2004), two further benefits can also be better *changeover quality* and greater *sustainability of improvements* (McIntosh et al., 2001, Culley et al., 2003, Mileham et al., 2004). Changeover quality describes the precision to which the equipment is reset, which has a potential impact across each of the distinct phases of a changeover, namely run-down, set-up and run-up (McIntosh et al., 2001, Smith, 1991). This impact is in terms of lost production and also the amount of scrap produced during a changeover (McIntosh et al., 2001). The impact of a high quality changeover will also continue into the production phase of the new batch, once the changeover has been completed (McIntosh, 1998).

4.6.1 New Equipment Design

The above discussion concerns the improvement of existing processes, individual machines or manufacturing systems. Beyond such retrospective improvement it is self-evident that a better changeover capability can be provided by the original equipment manufacturer (OEM) in a drive to create flexible process hardware from the outset. Although a comprehensive DFC methodology is not available, a number of design for changeover rules have previously been proposed (McIntosh, 1998, Van Goubergen and Van Landeghem, 2002) as listed in Table 4.1.

These rules can be used in a general sense to direct equipment design. However, they do not in themselves provide full guidance, since they fail to provide means to assess what the actual changeover capability of new equipment will be once in service. Equally the rules are unranked, where it is likely that, depending on the situation, some rules will have a far greater impact than others.

It has to be concluded that they do not match the coherence and structure of the widely used and also commercially successful DFX approaches particularly Design for Assembly (Boothroyd et al., 1994).

4.7 Conclusions

The chapter has discussed an operational definition of changeovers and the areas where resulting benefits of reduced changeovers can be sought. Different approaches to improving changeover performance which have previously been proposed in literature are reviewed. As part of this review changeover modelling and improvement techniques are analysed. The conclusions which can be drawn from the review are as follows:

- Previous work has highlighted the two extremes of changeover improvement approaches, namely organisational-led and design-led improvement. Various techniques have previously been proposed in literature which can be applied within these approaches. However, it becomes evident from the above discussion that there is no framework which encompasses all global changeover improvement opportunities within the organisation-design spectrum.

- Fundamentally all existing methods and techniques for changeover improvement are based on a retrospective-observational approach in analysing performance of changeover activities. This is due to their historical development as retrospective improvement tools as part of continuous improvement initiatives, where teams comprising shop floor and other personnel are analysing work practices and manufacturing equipment issues.

- The observational approach of the changeover improvement techniques found in literature is also reflected in the classifications of changeover activities by Zunker and Gest (Zunker, 1991, Gest, 1995). These classifications concentrate on what changeover personnel do, rather than analytically modelling what changes to the manufacturing equipment need to happen and what effort is involved in doing so.

- Although general design guidelines have been proposed these provide little guidance for original equipment manufacturers. This is partly due to the lack of evaluation criteria or metrics which can be applied to assess the changeover performance of a certain concept design.

The work presented in this thesis will address the gaps highlighted above in two ways:

1. A framework which encompasses all global improvement opportunities is developed (Chapter 5). The framework categorises primary improvement areas within the design-organisation spectrum of changeover improvement techniques. A selection of case studies is provided to validate the framework.

2. A Design for Changeover methodology is developed which is aimed to assist original equipment designers when designing new manufacturing hardware. As part of this methodology a changeover modelling technique, several evaluation criteria and metrics and a systematic improvement method are presented (Chapter 7-10).

5 A Framework for Global Changeover Improvement Opportunities

Many areas where changeover improvement can be sought have been identified in the literature, as discussed in the review of prior work in the previous chapter. However, the literature review has also identified the lack of a generic framework to identify global changeover improvement opportunities. It is the aim of this chapter to develop a framework encompassing all possible changeover improvement areas. Relationships between the various areas are described. Some smaller case studies are presented to illustrate the points made.

5.1 The complete changeover improvement landscape

From the discussions in the previous chapter it is possible to identify four primary areas where enhanced changeover performance of manufacturing equipment can be sought, namely people, practice, products and process (see Figure 5.1). In other words, a changeover is carried out by people following certain practices in order to changeover process hardware between different products. Opportunities for improvement are typically available in each of these primary areas. For optimal changeover performance to be achieved all areas need to be addressed within a changeover improvement initiative. This section describes the four areas in more detail and states the different aspects which are important when considering improvement in each area.

Figure 5.1 **Key areas when considering improvement of changeover performance**

5.1.1 People

Changeover performance in terms of time and the quality to which it is achieved can vary with the experience, motivation and skills of the changeover personnel. This is important for changeovers carried out on a day-to-day basis by shopfloor personnel (Mileham et al., 2004), but also when seeking to improve changeover performance (McIntosh et al., 2001).

Regarding the key areas mentioned directly above, the following issues have to be considered when seeking improved changeover performance in the People area:

- **Skills and Experience:** One important consideration in improving changeover performance is the skills and experience of the changeover personnel. The skills must be carefully matched with those required for a changeover. This might be done by targeted training sessions and personal development programmes, which are offered to personnel. As this is an issue which relies heavily on the human-machine interface, alteration of the machine might alternatively be used to reduce required skills. This will be developed as part of the DFC methodology later in this thesis.

- **Motivation:** The importance of motivated participants in changeover improvement initiatives is recognized in the literature (Sekine and Arai, 1992, McIntosh et al., 2001). Often it is suggested to achieve this by giving participants a sense of ownership of the initiative. In addition, developing an understanding for the usefulness of such an initiative by clearly identifying the benefits of improved changeovers for the company, but also for the individual is recognised (Productivity-Press-Development-Team, 1996). Equally, the motivation of changeover personnel when carrying out changeovers as part of their day-to-day job is important. Mileham et al. (Mileham et al., 2004) show how changeover performances vary between different shift teams. Although this might partly be due to differences in the skill set of the teams, differences in the motivation of the different teams is likely to be another reason for the discrepancies which are observed.

5.1.2 Practice

The area of practice encompasses all those improvement options where the way that work is conducted and how it is measured are changed. Also it incorporates all those changes to values, working environment and the culture prominent in a specific company or factory.

Key improvement aspects are:

- **Procedures and the way work is conducted:** The procedures with which personnel are provided and to which they should adhere can have an impact on changeover performance. Most SMED- or Kaizen-based improvement techniques predominantly address this aspect by externalising tasks, by changing the sequence of tasks, by standardising working procedures or by better preparation or visual aids (McIntosh et al., 2001, McIntosh et al., 2000, Shingo, 1985, Sekine and Arai, 1992). Standardised working procedures and better preparation are particularly important when seeking to externalise changeover tasks, ensuring that better practice is repeated from one changeover to the next. Also, optimising the task sequence such that walking distances are reduced by means of walking route analysis diagrams (Sekine and Arai, 1992), sometimes also called Spaghetti-diagrams (Schloz, 2006), is another improvement option in this area which reduces changeover time and enhances working conditions.

- **Allocation of resources:** Three aspects are important here. First, the allocation of products or product families to manufacturing resources. Sometimes Group technology or similar approaches are employed to group the manufacture of products according to their similarity on specific manufacturing hardware (Bicheno, 2003). Changeover sensitive scheduling can also provide huge benefits in terms of manufacturing throughput (Eriksson, 2006). Second, the allocation of labour resources to changeover tasks. The number of personnel allocated and balancing changeover tasks between personnel engaged in a changeover can greatly assist in improving changeover performance (Shingo, 1985, McIntosh et al., 2001). Third, the provision of other resources required by changeover personnel during a changeover, such as hand tools, to allow the changeover tasks being carried out in the most efficient way possible.

- **Measurements:** One factor which can facilitate ensuring that procedures are followed is a suitable measurement system which allows measuring changeover performance. Owen *et al.* (Owen et al., 2006) address particular issues with measuring when considering run-up.

- **Company values, culture and working environment:** A working culture is needed which promotes the importance of changeover performance and the adherence to working procedures, but also encourages the motivation and desire to continuously seek for improvements in the process and the work place generally (Bicheno, 2003).

5.1.3 Process

The process - or better the process hardware – refers to the manufacturing equipment which is changed over. Typically there is a range of settings available on a particular set of manufacturing equipment (McIntosh et al., 2001). The effort and time required to set these can depend strongly on how the process hardware can deal with variety in the product. Some researchers are looking into the improvement of the working envelope of mechanisms to be better able to deal with product variety (Matthews et al., 2006). Equally, the quality of change parts and the repeatability of their setting has an influence on changeover effort and time required (McIntosh et al., 2001). In general terms, changeover performance can be improved by increasing the tolerance of the process equipment to variability, for example variability in raw materials.

Many other aspects of the process can also be influential for example limited accessibility can inhibit carrying out changeover tasks efficiently. Also, through good layout of machine centres or working stations, quick changeovers can be facilitated by reducing walking distances between subsequent taks.

There are further, more detailed aspects which need to be considered here for specific changeover activities such as assembly or disassembly. Some of these will be described in Chapter 6 as part of the review of DFX methods.

5.1.4 Products

Likewise, there are aspects of the product which can have a significant influence on changeover performance. These include the product range requirements, variation of raw material and between individual products and features arising from product differentiation.

The key areas in which changeover improvement is influenced by design of the product are:

- **Product differentiation:** Products range between the extremes of those which are mass manufactured and therefore are standardised, and those which are personalised and built-to-order. Standardisation of products or product features is often used as one way to reduce - or in some case eliminate altogether - variation and thus minimise impact on changeover. Alternatively, various routes are available if a company chooses to offer increased product differentiation or personalised products. For example, this can happen by designing personalised services around a standardised product (described in Chapter 2). Alternatively, modular design and product platform design potentially offer huge benefits by allowing postponement of product differentiation through assemble-to-order manufacturing (Bicheno, 2003). Some of these concepts, such as modular design, standardisation and product platform design, can equally be applied on the process design and are reviewed in Chapter 6.

- **Robust Design and Tolerance Design:** Work has been conducted to evaluate whether specific product quality or tolerances be loosened without comprosmising customer perception of the product's functionality, which can for example be achieved using Design for Six Sigma (Bicheno, 2003). An example of a printing line is reported by McIntosh *et al.* (McIntosh et al., 2001), where a slight reduction of required print quality would make possible the use of a different ink system, which in turn would eliminate the need for ink changes.

- **Quality of raw materials:** Material properties can be a further issue, particularily when used to differentiate properties of the product. An example for this would be the variation of material properties in injection molded parts when different plastics or even different colours are used. Mould and post-moulding process settings need to be able to compensate for this variation. Alternatively, minimising the variation of raw material quality can be critical to ensure a good changeover performance (McIntosh et al., 2001).

5.1.5 Changeover Improvement – Adressing issues in all 4P areas

It becomes evident that for optimal changeovers to be achieved during a changeover improvement initiative it is important that all four areas, namely people, practice, products and process are considered and appropraitely addressed. The way products and the process are designed have important implications on possible changeover performance. However, once product and process designs have been chosen, it is important that ideal procedures are defined as targets, that people's skills, experiences and motivation are matched with the procedures and that measurements are put into place that monitor the performance.

This chapter goes on to describe some of the implications product and process designs have on possible changeover performance. Also, the major relationships between the various areas in the 4P framework are discussed. It will also be described in how the aspects discussed in this section can be taken into account when seeking improved changeover performance.

5.2 Design-led vs. Organisational-led Changeover Improvement

Some differences in design-led and organisational-led improvement have been discussed in the review of prior work on changeover improvement in the previous chapter. For example, McIntosh *et al.* argue that there is a design-organisation spectrum in which changeover improvement initiatives can be biased towards either organisation- or design-led improvements (McIntosh et al., 2001). This section will adopt these concepts and differentiate between improvements through design (i.e. designing or re-designing) and organisation (i.e. organising or re-organising).

Organisation- and design-led improvements can be associated to the four areas which influence changeover performance described in the previous section as shown in Figure 5.2. Thus, improvement through design affects the products and process areas. Improvement through organisation affects people engaged in changeovers and the practices they adopt.

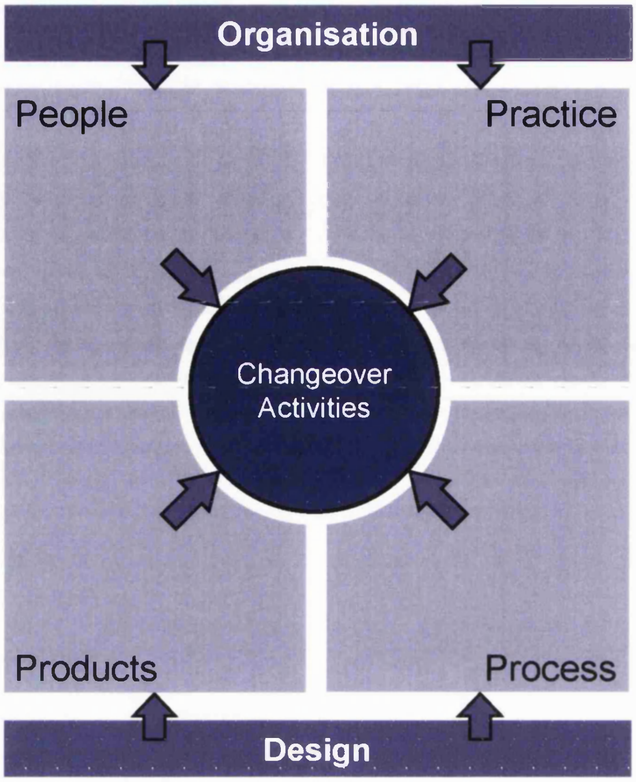

Figure 5.2 **The '4Ps' of Changeovers – Influence of Design and Organisation on Changeover Performance**

5.3 Case Study 1- Limits to organisational improvement

A case study was carried out with a company in the food industry[2]. Specifically the company was packaging frozen fruits and vegetables. The two main changeover issues were the required clean down of the machinery and changing of the packaging material (Bado, 2005). Besides packaging food for their own brand, the company was mostly packaging frozen food for a variety of supermarket brands.

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[2] The case study was carried out as part of a MSc thesis by A. Bado (2005). Main aim was the development of a financial benefit assessment tool. As part of this, cost/benefit-analyses were carried for various design improvements on a frozen food packaging line. The design improvement options were compared to possible organisational improvements. It is this part of Bado's work which is presented in this section.

Individual packaging for this variety of different brands requires numerous changes to the manufacturing equipment. In cases where only packaging size changes between different products, different machine settings require adjustment. Other packaging designs require the addition of extra machines, for example for layered filling of plastic containers with a variety of different fruits. The specific line under consideration is shown in Figure 5.3.

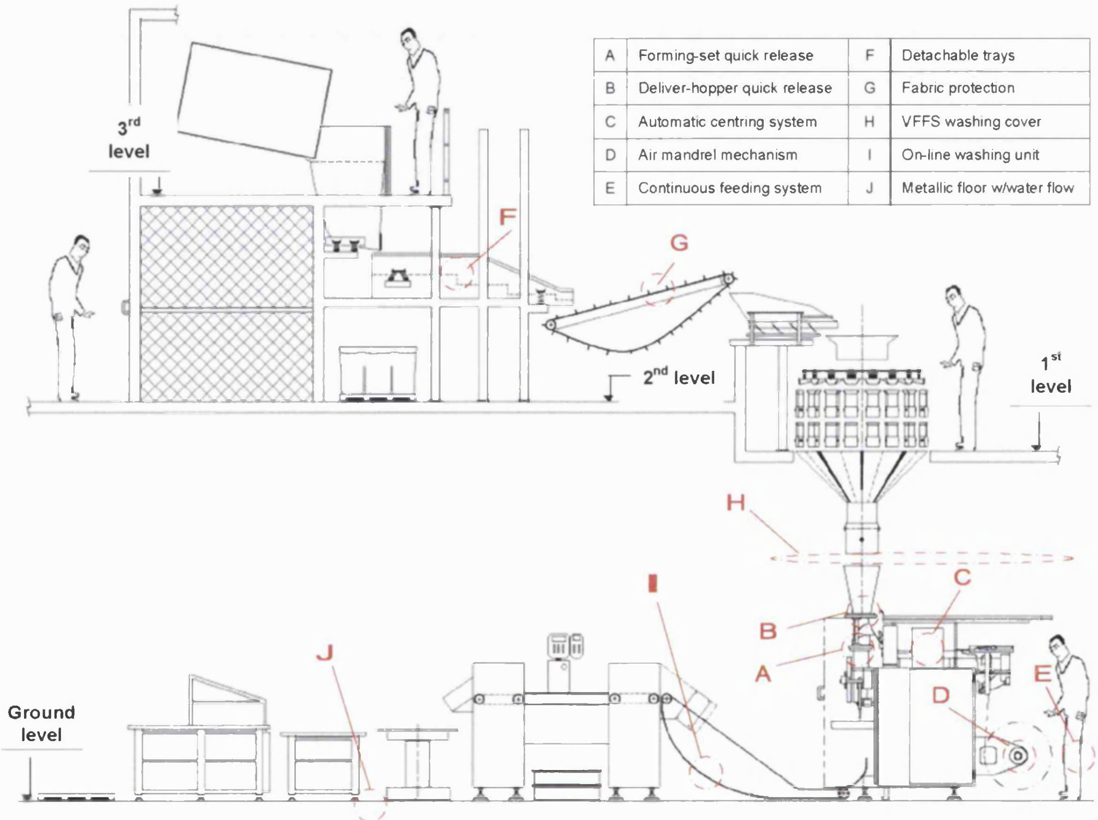

Figure 5.3 Frozen food packaging line layout with highlighted areas where improvement opportunities have been identified (Bado, 2005)

One objective of the case study was to show the difference in possible improvements when comparing design-led improvements with purely organisational improvements (Bado, 2005). Figure 5.4 shows a list of organisational and design improvements suggested during the case study. The improvements suggested included for example changing the task sequence such that walking distances are reduced. Also, the re-assignment of labour resources to changeover activities and the introduction of better working practices were suggested. It was believed that changeovers could possibly be reduced by about 15min or

19% through the implementation of these organisational changes. However, it was felt unlikely that significant more improvement could be achieved beyond this by purely organisational changes.

The student who carried out this case study was asked to contrast the organisational improvements with possible design changes. A range of design improvements were suggested (Bado, 2005). The improvement options were aimed at various sections of the line shown in Figure 5.3. A list of the design improvements suggested, together with estimates for possible changeover reduction, improvement cost and ease of implementation is provided in Figure 5.4. It was estimated that changeover time could - on top of the previously mentioned organisational changes - be reduced by a further 48min through these design improvements. Together with the organisational improvements this equates to an overall improvement of 82% compared to the original changeover (see Figure 5.5).

Level		Proposed improvements	Sketch	Total CO reduction	Ease of implementation	Relative cost
Organizational		• Labour resources re-assignment • Reduce walking movements - change task sequence • Shorten taks by better practises	-	-15	easy	no cost
Design	*Tooling*	• Forming-set quick release	A	-3	easy	low
		• Hooper delivery quick release	B		easy	low
	Equipment	• Automatic centering system	C	-31	medium	medium
		• Air mandrel mechanism for film-reel positioning	D		medium	medium
		• Continuous feeding system **(1)**	E	-4	medium	medium/high
	System	• Duplicate detachable trays of vibration table	F	-14	easy	medium
		• Top-conveyor fabric protection	G		easy	low
		• VFFS machine washing cover	H		easy	low
		• On-line finished-bags conveyor washing-unit	I		medium	medium
		• Metallic grilled floor w/water curtain to sweep dirt **(2)**	J		difficult	N/A
	Product	• Reduce bag width variety (standard bag widths)	-	N/A	medium/difficult	N/A

Sum of potential CO time-reduction = -63 mins

Notes:

(1) This design proposal applies to film and bag changeovers. It does not significantly contribute to reduce the product changeover duration. If implemented waste could be reduced in approx. 85%.

(2) Difficult to implement retrospectively. However, this improvement proposal could be considered for the specification of new facilities.

Figure 5.4 Summary of improvement proposals and their impact (Bado, 2005)

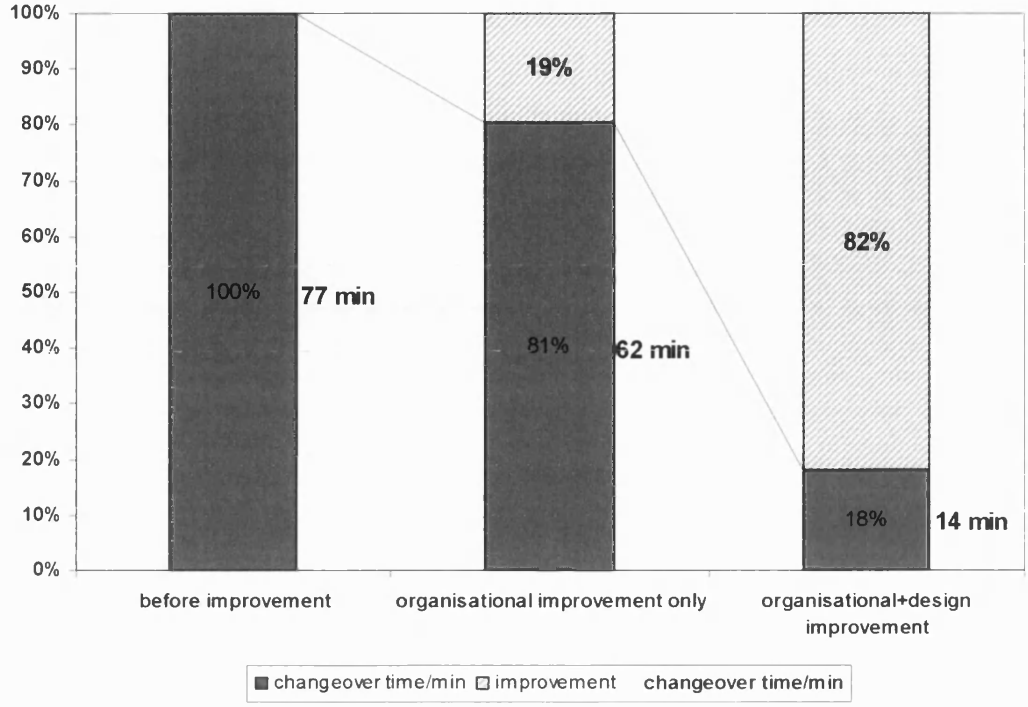

Figure 5.5 **Comparison of organisational only improvement with design-led improvement**

5.4 Retrospective improvement vs. OEM re-design – Limits to retrospective improvement

In this section it is described how approaches for retrospective improvement initiatives and OEM re-design differ and what aspects need to be considered. It is for example more likely to be difficult to make major design changes within a retrospective improvement initiative, due to considerations of aspects such as cost and time to implement and other important reasons (McIntosh et al., 2001). The feasibility of design changes in a retrospective environment is likely to be more influenced by, for example, the quality of the available financial benefit assessment, the cost of improvement, the willingness of the company to invest in manufacturing flexibility and the required time to implement design changes (McIntosh et al., 2001, Bado, 2005). This is illustrated in Figure 5.6. As a result the amount of re-design of products and process which is carried out as part of retrospective improvement initiatives is often limited (McIntosh et al., 2001).

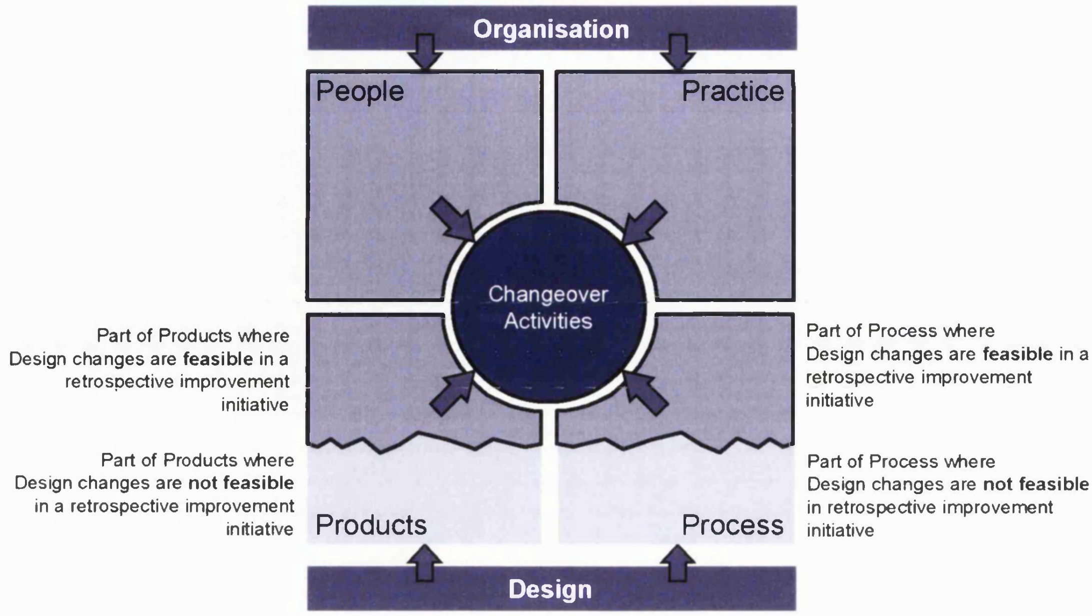

Figure 5.6 Schematic illustration of the fact that feasibility considerations often limit possible design improvements in a retrospective improvement initiative

5.4.1 Case Study 2 – Limits to retrospective improverment

Two major European automotive manufacturers were visited during the author's work on this project and changeovers on large stamping presses producing panels for motor cars were witnessed at both factories. Both companies had previously carried out changeover improvement programmes. This section will describe the observations made during these visits and compares them to a similar example reported from the Japanese automotive industry.

Considerable variation between changeover times of similar presses has been found at the two European automotive plants, which were visited. Company A, with large stamping presses of 15 MN to 28 MN size, aimed to achieve the vision of "Every part – every day". Therefore, the company required the ability to perform constant and reliable changeovers with minimum run-up. A changeover improvement initiative was performed and changeovers on the 6 presses under consideration were reduced from an average of about 30min to about 20min.

Another European manufacturer, Company B, reduced changeover times of six transfer presses (of similar size to those at Company A) during a 9 month project from an average of about 16 min to about 8min. The fastest changeover achieved after the improvement took 7.56 min. A changeover witnessed by the author took 8.31 min. The die change alone consists of about 48 steps, of which 15 are performed manually and 33 are automated steps. In an effort to increase manufacturing capacity the company used a SMED-based approach to reduce changeover times. Part of the exercise was externalising as many changeover activities as possible and streamlining of both external and automated steps.

Both companies are seeking to improve their changeover capabilities, as pressure to run smaller batches and increased product variety is rising. Indeed this need for improved changeover performance comes apparent when comparing their manufacturing flexibility with the flexibility available at Hirotec, a Japanese automotive part manufacturer. Besides supplying automotive parts to car manufacturers around the world, Hirotec is also OEM for stamping presses and tooling. On its webpage Hirotec reports of its successes in reducing changeover times. The company claims to have successfully reduced changeovers from many hours in the late 1970s to repeatable 30 seconds in 2000 (as shown in Figure 5.7) (Hirotec, 2004). This claim was validated by the production manager of Company A, who was able to witness a changeover at Hirotec during a company visit as part of a training course on the Toyota Production System (TPS).

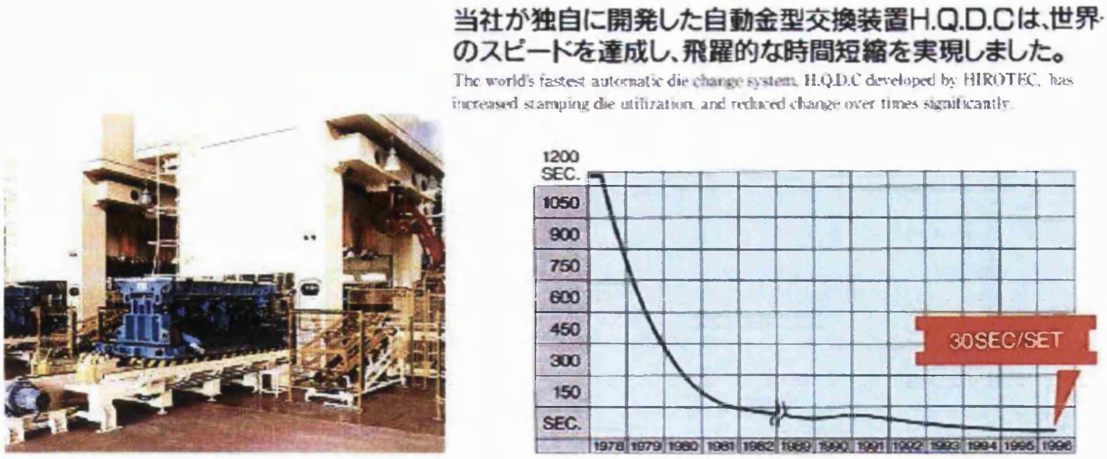

Figure 5.7 **Hirotec's success in reducing changeover time significantly (from Hirotec web page (Hirotec, 2004))**

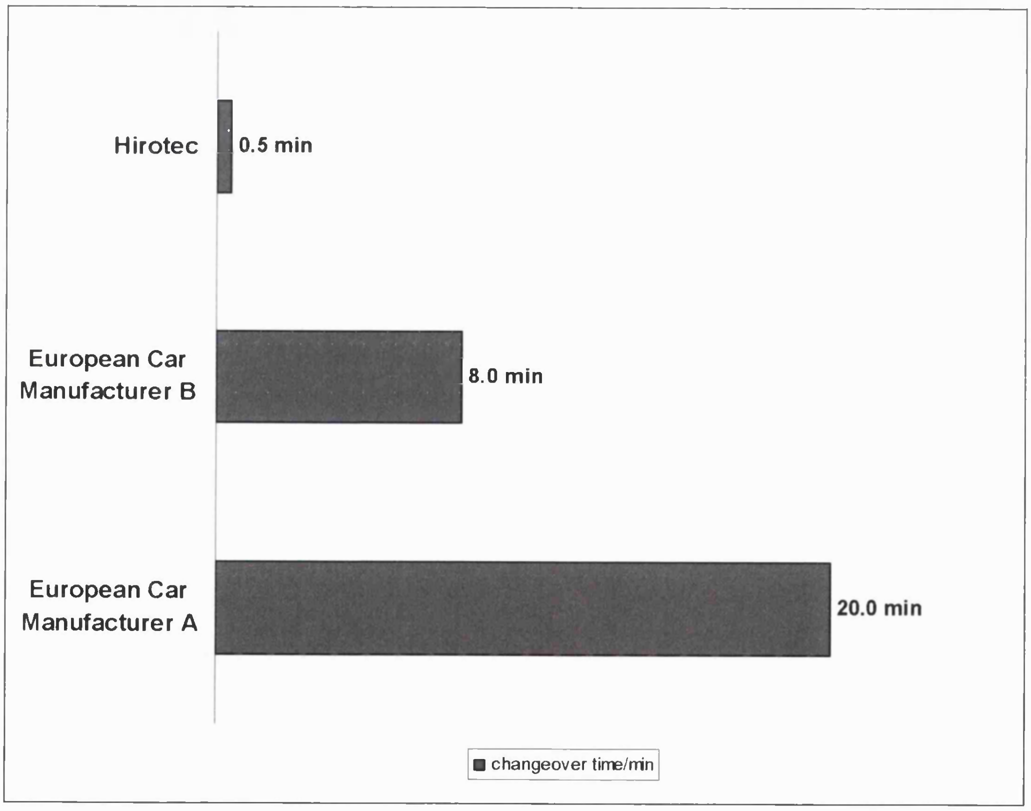

Figure 5.8 **Comparison of changeover performances at the two visited European stamping plants with the performance of the Japanese automotive supplier, Hirotec**

Two things can be learnt from the comparison above. First, Hirotec has put strong and continuous efforts into the improvement of changeovers on their stamping presses over the last 3 decades. Second, the changeover capabilities of the two European automotive manufacturers are still far behind those of the Japanese manufacturer Hirotec.

But what are the issues that cause the inferior changeover performance at the European car manufacturing plants visited by the author? Through the author's discussion with employees of the two European companies the following general issues could be identified:

- **Space issues.** Layout of plant and presses inhibited access and more optimal handling of press tools
- **Parallel activities not possible.** There are two areas where parallel working could be used in the European companies which are currently not employed due to the design of the equipment. Firstly, new dies could be replaced from one side, while old dies are taken out on the other side simultaneously. Secondly, changeover of early presses in the line could start while later presses are still in production. This would require separately operated presses and revised safety measures for the individual presses
- **Monitoring of changeovers and constant strive to improve.** Some preliminary measures were introduced with some success at Company A and B, but these need to be refined
- **Retrospective focus of changeover improvement initiatives.** There is no long term strategy as to how to include changeover performance in the specification of new equipment bought in the future

Considering the vast differences, it becomes clear that the European manufacturers are facing extreme challenges if they want to remain competitive in a market where on time delivery of a wide product range in small batch sizes is absolutely key in satisfying customer demands. Clearly Hirotec was greatly assisted in its efforts to increase changeover performance by the fact that it is its own original equipment manufacturer. Problems with the equipment could easily be fed back to the in-house designers and changes to manufacturing equipment could be taken on board more easily.

5.5 The need for integrated improvement through design and organisation

The previous sections have shown how important design is when seeking optimal changeover performance. This is not to say that design improvements are better than organisational improvements, but that the balance between organisational and design improvements is important. This balance might change noticeably depending on individual circumstances. This section presents a brief industrial example where design improvements have been made, but the improvements diminished over time. Reasons for this deteriorating performance are given and it is discussed what needs to be done in such situations to ensure sustainable improvements.

As part of this research programme, the author spent some time at an automotive supplier specialised on machining high precision parts. During this time changeovers were investigated on a particular type of CNC machines which were used to manufacture journal bearings. The company had previously carried out a changeover improvement initiative on these machines with some success. However, it was realised that although some improvements have been sustained other improvement ideas had never been implemented or new personnel had stopped using the new working procedures that had been introduced.

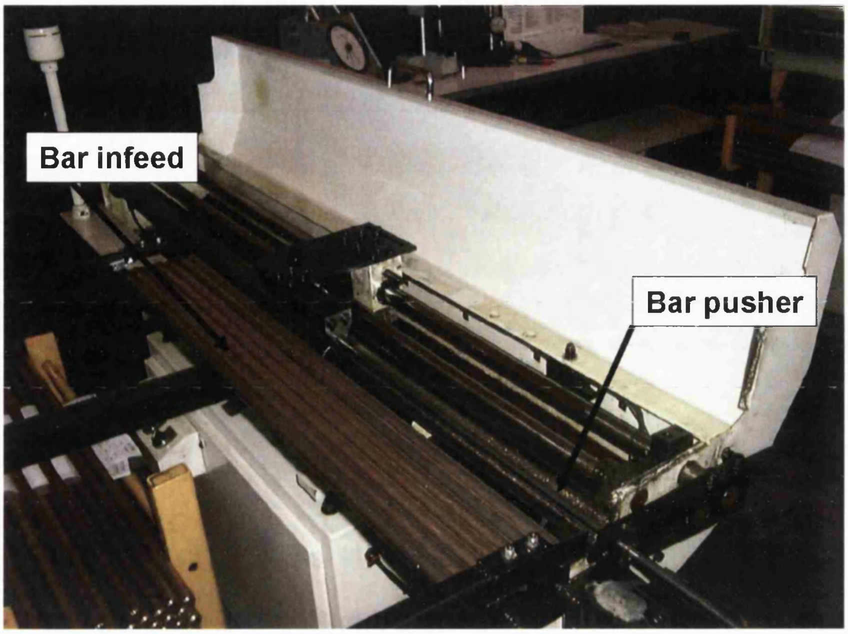

Figure 5.9 Bar feeder for CNC machine centre

One particular improvement was a very simple design alteration to the bar feeder shown in Figure 5.9. To adopt the bar feeder to different bar sizes, the whole bar pusher had to be taken off the machine and replaced by a pusher for the new bar size. This changeover of the bar feeder took 45 min. After the improvement only a small cap had to be added or removed from the pusher reducing bar feeder changeover time almost completely and saving 2.8 hours of equipment downtime per week.

Although the new way of changing the bar feeder was an effective way to change from one diameter to another, the new approach had not been continued. It was important to establish what had happened and a number of interviews with the company's personnel were held. Thus, in conversation with engineers and changeover personnel the following reasons for this poor situation were identified:

- The improvement had been successfully trialed on one CNC machine centre, but had never been implemented on other similar machines. Hence, there were two possible ways to change those machines over. The old way for all machines without this idea implemented and the new, improved way for the one machine with the improvement implemented. However, both procedures were possible on that particular machine with the idea implemented. After some time the improvement got lost when changeover personnel discontinued to employ the new, improved way and returned to using the old changeover procedure on all machines

- New changeover personnel were employed on the particular section of the factory. The new personnel were not informed of the improvement on one of the machines

This shows how design and organisational improvements are often interlinked. In particular it shows the difficulties which come along with new personnel, lack of sufficient training and lack of changeover monitoring. However, it also shows how these difficulties can be worsened when improvements based on design alteration still allow old operating procedures to occur.

This work supports the author's claim that it is important that all 4P areas are considered when undertaking changeover improvement initiatives (independent of whether it is a retrospective or OEM re-design initiative), as an improvement in one area is likely to require changes in other areas and necessary actions need to be undertaken in order to attain and then sustain full improvement. The case studies in this section have shown that when improvement has been undertaken in the design of process or products, the areas of practice and people have to be aligned accordingly. This can mean that standard operating procedures need to be updated, or training needs to be provided to get people's skills to the required levels.

5.6 Conclusions

This chapter has introduced the 4P framework which depicts the influence of organisation of people and practice, and the influence of design of process and products on changeover activities. The literature suggests that finding the right balance between design-led and organisational-led improvement initiatives is difficult and is – in the case of retrospective improvement programmes – often tending towards the low cost, quick-to-implement improvements (McIntosh et al., 2001). Equally it is important that equipment designers are aware of the impact of their decisions on possible "best practice operation" of their equipment. Rather than a step-by-step method, the 4P framework gives a structure to global changeover improvement areas. A selection of small case studies has been presented in the chapter to support the importance of a balanced improvement effort between the 4 areas, people, practice, products and process.

6 State of the Art in Design of Changeable Manufacturing Systems

In Chapter 2 changeoverability is defined within the concept of changeable manufacturing systems. Previous chapters have identified the need for changeoverability in modern manufacturing systems. Global changeover improvement opportunities have been identified and the importance of designing changeoverability into manufacturing equipment from the outset in order to reach optimal levels of performance has been recognised.

This chapter reviews design methodologies which are relevant to the development of a Design for Changeover Methodology presented later in this thesis. In general relevant design methodologies can be categorised into two areas: Those methodologies which seek ***to reduce or isolate the impact of variety*** *on the design artefact and those methodologies which aim* ***to improve changeover related activities****.*

Amongst those methodologies which aim to improve changeover related activities reviewed in this chapter is the most prominent Design for X (DFX) methodology Design for Assembly (DFA). In the area of design methodologies which aim to reduce or isolate the impact of variety the reviewed methodologies include for example modular and platform design, Axiomatic Design (AD) and more specific methodologies for the design of changeable manufacturing systems.

This chapter will review relevant methodologies in both areas and will discuss gaps and shortcomings. Based on the shortcomings of available methodologies the chapter concludes with the detailed aims and scope for the DFC methodology developed in this thesis.

6.1 Reducing or isolating the impact of product variety

A variety of approaches which seek to reduce or isolate the impact of product variety on the design artefact can be found in the literature. Those design methodologies can be grouped into two fields: General engineering design approaches, which seek to facilitate product variety in the design artefact using intelligent product architecture, and methodologies which are specifically aimed to support the design of changeable manufacturing systems. This section will review relevant design approaches in both fields.

6.1.1 General engineering design approaches for product variety

The section begins with the description of general concepts in the area of product families. This includes a general description of product variety and how it can be achieved through intelligent product architecture and structure using modular product design or platform design. Some design methodologies which seek to increase product variety or reduce the impact of product variety on product design are also reviewed. This includes methodologies such as design for variety, adaptable design and Axiomatic Design (AD) (Martin and Ishii, 2002, Gu et al., 2004, Suh, 2001).

Product Variety, Architecture and Structure

Ulrich (Ulrich, 1995) defines ***product variety*** as "the diversity of products that a production system provides to the marketplace". As such, product variety can have two dimensions which are often referred to as spatial and generational variety (Martin and Ishii, 2002). Spatial variety is the breadth of products under offer at a given time (Fischer et al., 1999). Generational variety describes changes between different product generations and can be used to describe the rate at which existing products are replaced (Fischer et al., 1999).

The ***product architecture*** allocates functions of the product to physical components (Ulrich, 1995). The ***product structure*** describes the structure of components and their relationships in a product. An example product structure for an office chair is shown in

Figure 6.1. Within a product architecture product variety can be achieved on two levels, the level of the product structure and on the component level.

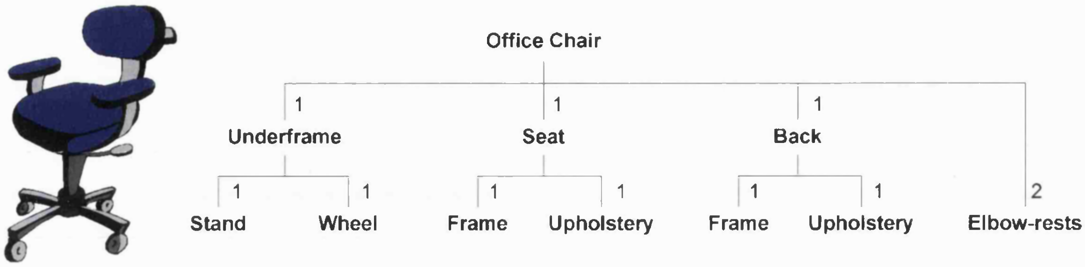

Figure 6.1 Product Family Structure of an office chair. Example taken from Erens (Erens, 1996)

Modular product design is often used to cost effectively achieve the required product variety on the product structure level through intelligent product architecture (Ulrich, 1995, Erens, 1996, Fischer et al., 1999, Whitney, 2004). The variety of the product is then given by the variety of its subassemblies and components. On the component level variety is constituted by differing features and values for feature parameters.

Product variety is often described using so called product parameters or product characteristics (Erens, 1996, Neuhausen, 2001). Erens (Erens, 1996) defines a product parameter as a "variable quantity or quality that makes a product family specific. Parameters are used to derive a product variant from a product family, but also to make a product feature specific for its application." A selection of sample product parameters for an office chair product family is given in Figure 6.2. In the figure the parameters are presented as part of a choice-sheet, based on which product variants can be instantiated.

Figure 6.2 Choice-Sheet with Product Parameters for the instantiation of a product variant. Example taken from Erens (Erens, 1996)

Modular Product Architecture

A design is defined as modular, when one function is allocated to one technological module (Erens, 1996, Ulrich, 1995). In comparison to an integral product design, this reduces the impact of changing functional requirements on the product design and manufacturing operations (Ulrich, 1995).

There are three different types of modular product architecture, namely slot, bus and sectional. The difference between these types lies in the way in which component interactions are organised. In the case of slot modularity, there is only one specific physical interface for each ‘slot’, preventing component variants of different types from being interchanged (e.g. automobiles, where radio and speedometer have different types of interfaces with the instrument panel). In the case of bus architecture all interfaces are the same and all components are connected to one common component (e.g. electronics or roof racks). In a sectional architecture interfaces are all the same, however, there is no single element to which all other components are attached (e.g. piping systems or Lego™ bricks). The difference between the three types of modular architecture is illustrated in Figure 6.3.

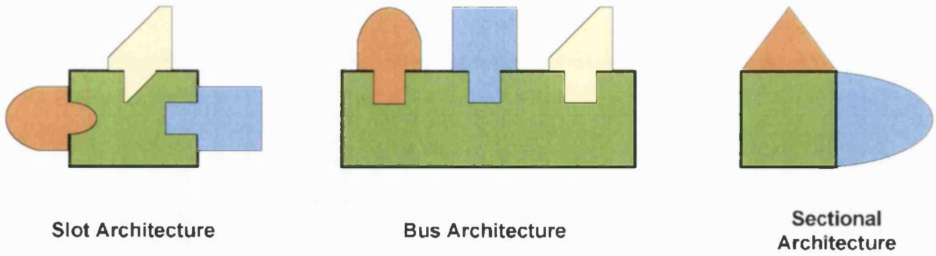

Figure 6.3 Three types of modular architecture (Ulrich and Eppinger, 2000)

Standardisation of interfaces plays a central role in modular architecture. Once standardisation of interfaces for certain types of components has been achieved, component swapping, component sharing, cut-to-fit modularity and mix modularity are approaches which can be used within the modular design philosophy to increase product variety while minimising the impact on manufacturing operations (Ulrich, 1995) (see Figure 6.4).

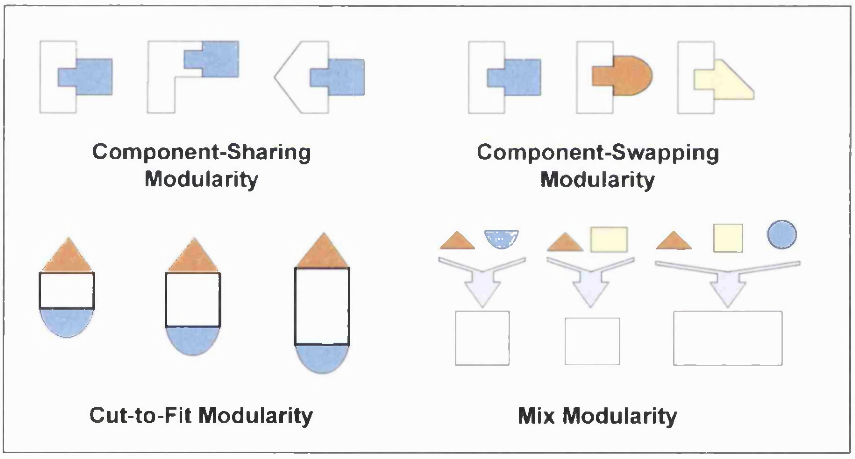

Figure 6.4 Types of Modularity (Ulrich, 1995)

Product Platform Design, Design for Variety, Adaptability and Modularity

Research on product platform design is seeking to address issues arising from increased customer demand for product variety, shorter time-to market and ever decreasing product life-cycles (Herrmann *et al.*, 2004). A product platform is "an architectural concept comprising interface definitions and key-components, addressing a market and being a base for deriving different product families" (Erens, 1996). The aim is to develop a platform of stable elements which are shared between products or even product families (Meyer and Utterback, 1993, Erens, 1996).

Design for Variety (DFV) aims to reduce time-to market by addressing generational product variation (Martin and Ishii, 2000, Martin and Ishii, 2002). Martin and Ishii (Martin and Ishii, 2000) developed indices for generational variance to help designers reduce development time and cost of future evolutionary product design.

Gu (Gu et al., 2004) proposes a methodology called Adaptable Design which seeks to increase product functionality by increasing the product's adaptability. Product architecture is critical for a product's adaptability. Adaptable Design is seeking improvement by segregating the product architecture using platforms, modules and adaptable interfaces.

Axiomatic Design

Axiomatic design divides the design world into four different domains: customer domain, functional domain, physical domain and process domain (Suh, 1990). This is illustrated in Figure 6.5. The customer domain captures the individual customer needs that the customer is looking for. The functional domain specifies the functional requirements for these customer needs. In the physical domain, design parameters are specified to satisfy the functional requirements. Finally, process variables are chosen in the process domain to produce the specified design parameters. It becomes apparent that there are distinctive relationships between individual elements of different domains. These relationships or mappings are formed by the designer during the design process. For each mapping the element in the domain on the left of a mapping relationship represents 'what the designer wants to achieve', the domain on the right represents 'how it is achieved' (Suh, 2001).

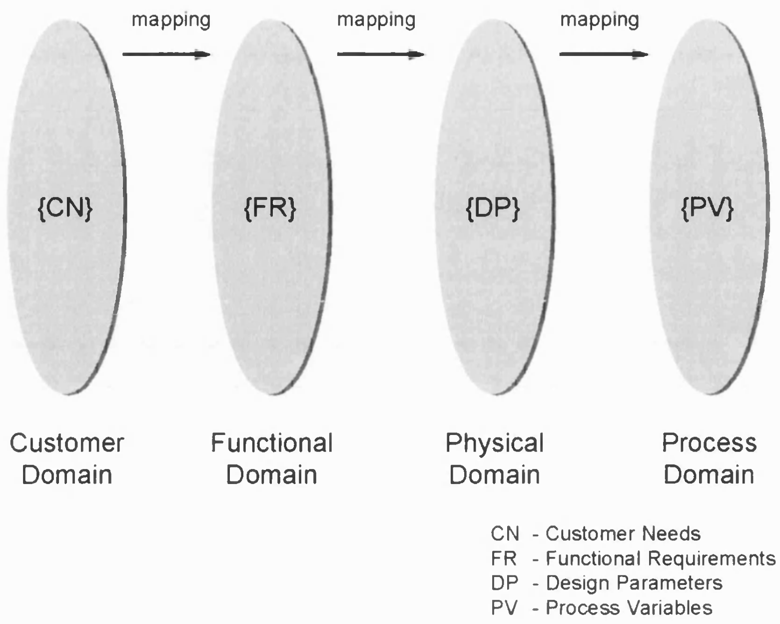

Figure 6.5 The four domains of the design world (Suh, 2001)

According to Axiomatic Design (AD) the chosen Functional Requirements (FRs), Design Parameters (DPs), Process Variables (PVs) and the mappings between them need to satisfy two principle axioms:

> ***Axiom 1:*** **The Independence Axiom.** Maintain the independence of Functional Requirements (FRs)

> ***Axiom 2:*** **The Information Axiom.** Minimise the information content of the design

Suh (Suh, 2001) provides many case studies of product, process and software design which follow this process and claims that "the performance, robustness, reliability, and functionality of products, processes, software, systems, and organizations are significantly improved when these axioms are satisfied".

Together with the general design concepts of modularity, platform design, Axiomatic Design has provided the basis for many design methodologies which aim to support equipment designers when designing changeable manufacturing systems. A selection of these is reviewed in the following sections.

6.1.2 Design of Changeable Manufacturing Systems

One focus of current research into manufacturing systems is the design of changeable and reconfigurable manufacturing systems which better react to variations in product characteristics, product mix and volume. This is often attempted using modular design approaches. Eversheim and Neuhausen (2001) for example propose a Modular Plant Architecture (MPA) to increase a company's ability to react to changes in change drivers as described in Chapter 2. The idea behind this and other approaches is to use the independence axiom of Axiomatic Design to minimise and isolate the impact of change drivers on specific production objects. The target is a modular plant architecture which represents an uncoupled or de-coupled design as shown in Figure 6.6.

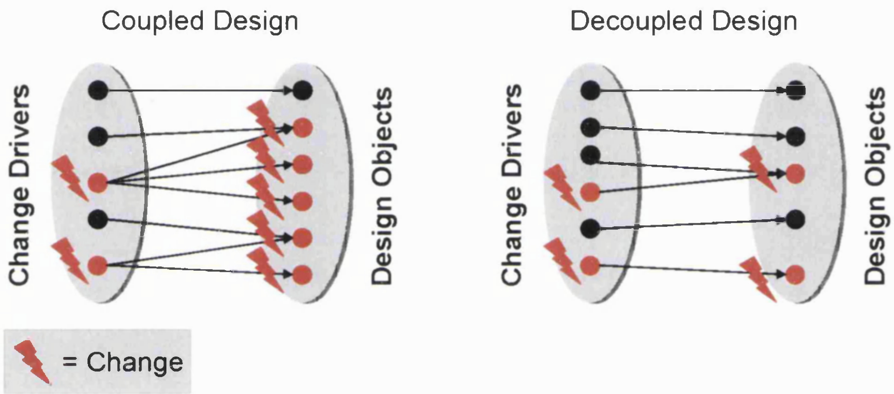

Figure 6.6 Coupled and De-coupled Design (Eversheim and Neuhausen, 2001)

Relevant approaches in this field are:

- Design of an agile manufacturing workcell
- Design principles for Reconfigurable Manufacturing Systems (RMS)
- Design of modular production systems
- Design for changeability

These approaches will be reviewed in more detail in the following sections.

Design of an Agile Manufacturing Workcell

Quinn *et al.* (1996) developed an agile manufacturing workcell for light mechanical assembly applications. Their aim was "to accomplish rapid changeover from the assembly of one product to the assembly of another product". For this purpose an example robot workcell was designed. The workcell makes use of flexible belt feeders which only require changeovers in rare cases when for example component shapes vary considerably. The point of delivery of the component is not critical, as the robot is guided by a vision system which detects the position of fed-in components. A parameterised programming approach has been used for the vision system such that new shapes can easily be programmed reducing the time to set-up the workcell for a new product. Rapid changeover is also achieved by a modular gripper system. Quinn *et al.* (1996) advocate a concurrent engineering design approach when designing grippers for different components. This way it might be possible to find a design such that two components of different shape can be picked up by the same gripper.

Reconfigurable Manufacturing Systems and reconfigurable machine tools

Koren proposes Reconfigurable Manufacturing Systems (RMS) to achieve cost-effective response to market changes, combining the high throughput of dedicated manufacturing lines with the flexibility of Flexible Manufacturing Systems (FMS) (Koren et al., 1999). This is schematically illustrated in Figure 6.7.

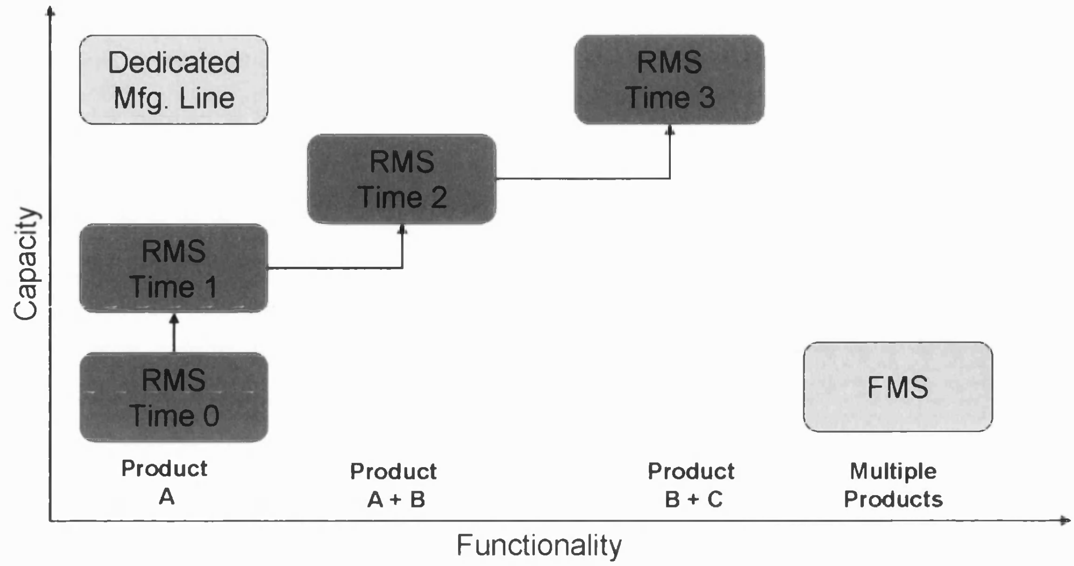

Figure 6.7 Functionality and Capacity of a RMSs compared to dedicated manufacturing lines and FMSs (Koren and Ulsoy, 2002)

An extensive amount of research has been carried out on Reconfigurable Manufacturing Systems by Koren, Ulsoy, Mehrabi *et al.* (Koren *et al.*, 1999, Koren and Ulsoy, 2002, Mehrabi *et al.*, 2000). As part of this work they have identified six core characteristics of a RMS:

- **Modularity**: Design all system components, both software and hardware, to be modular
- **Scalability**: Design the system such that production capacity can easily be changed by rearranging the existing production system and/or changing the production capacity of reconfigurable components (e.g. machines) within that system
- **Integrability**: Design systems and components for both ready integration and future introduction of new technology
- **Convertibility**: Allow quick changeover between existing products and quick system adaptability for future products

- **Customisation**: Design the system capability and flexibility (hardware and controls) to match the application (product family)
- **Diagnosibility**: Identify quickly the sources of quality and reliability problems that occur in large systems

Furthermore, Koren and Ulsoy (2002) provide a list of principles the design and operation of a RMS need to satisfy in order to achieve cost-effective and rapid reconfiguration:

1. To enhance the responsiveness the RMS core characteristics need to be embedded in the entire system as well as in its components
2. The RMS contains adjustable production resources to respond to change to the requirements for capacity and functionality
3. The RMS is designed around a part family, with the just the flexibility to produce all parts of the family
4. The RMS contains an economic mix of dedicated, flexible and reconfigurable machine tools, whose functionality and productivity can be readily changed when needed
5. Continual monitoring and diagnostics needs to be embedded in the RMS to enhance response to fault or quality/productivity degradation
6. In general, shorter manufacturing systems with a smaller number of stages are more reconfigurable, but require higher investment cost in machine functionality
7. In general, systems with a large number of alternative routes to produce a part are more reconfigurable, but they require higher investment cost in the material handling system

8. The RMS possesses cost-effective safety capacity and stand-by functionality that is utilised to cope with unpredictable events.

9. Decision-making capability is embedded in the RMS to reduce its response time to unpredictable events

10. The organisation of the manpower that operates the RMS is structured according to the RMS core characteristics and includes people and teams (modules) that are dedicated to particular tasks as well as people and teams that are flexible in their assignments.

Design of Modular Production Systems

Neuhausen (2001) developed a methodology for modular production systems to reduce the impact of product variety on the production process. The production process is considered on three different levels: the level of the **production line**, the level of **production stations** and the level of **production processes** (as shown in Figure 6.9).

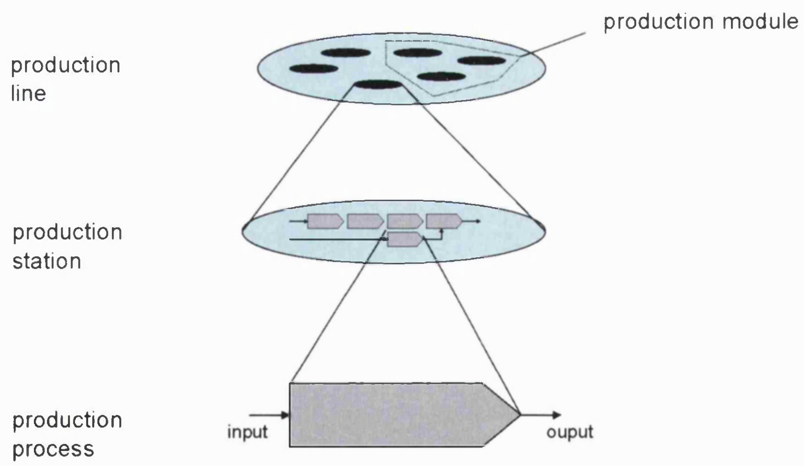

Figure 6.8 Three levels of a production line analysed by Neuhausen (Neuhausen, 2001)

As part of the methodology, design improvement strategies are suggested on the top two levels. The aim of the suggested strategies is to reduce the impact of product variety on the overall performance of the production system. On the production line level this is achieved by postponing variation into final assembly or by isolation of variation into separate pre-assembly lines.

On the level of production stations Neuhausen proposes a Production Structure Matrix (PSM) which maps the product characteristics of products and components to required changes of processes and stations. The three key areas in the matrix are the product description, the process description and the mapping area. An example PSM is illustrated in Figure 6.9.

In the product description the number of variants and the frequency of change of products, component and their product characteristics is taken into account. The process description represents the production line structure, the associated stations and processes. The number of change parts and tools and the number of settings can be specified on a per process basis. Furthermore it can be specified whether these changes and settings are carried out manually or automatically.

In the mapping area the relationships between product characteristics and processes are specified. Neuhausen distinguishes between changes in product characteristics which require changing of tools or parts and changeovers which require changes to other settings. This is indicated in the mapping area of the matrix by a black or grey field, respectively.

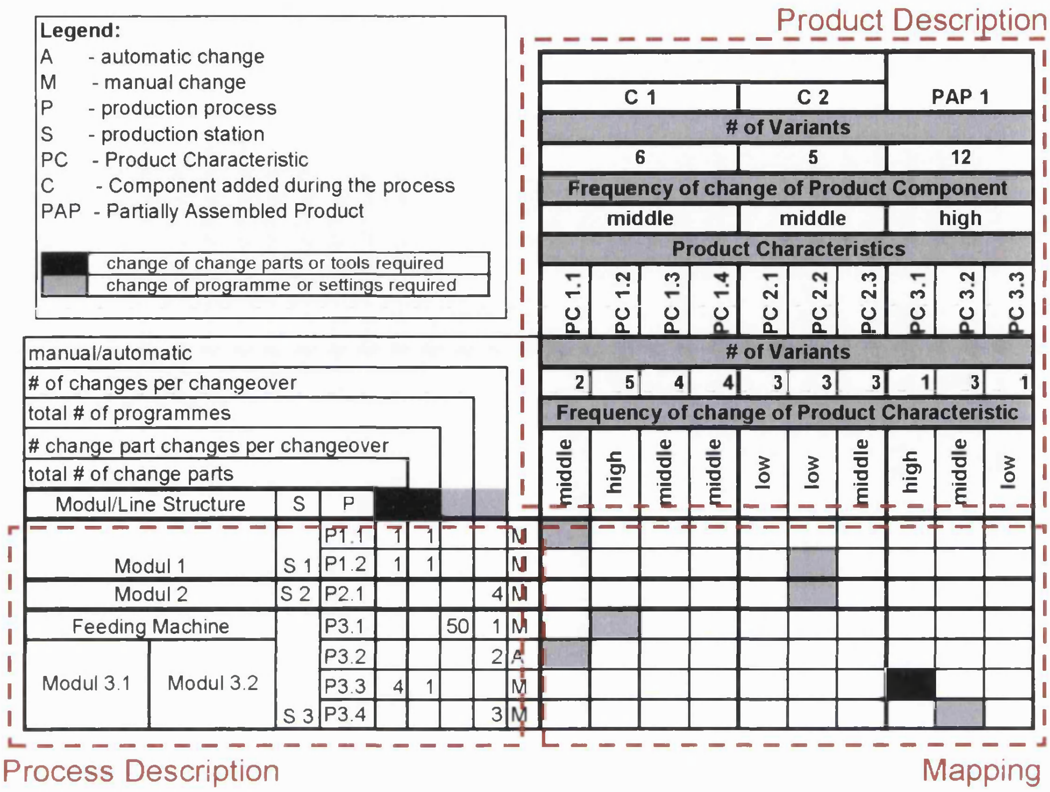

Figure 6.9 **Production Structure Matrix (PSM) according to Neuhausen (Neuhausen, 2001)**

Based on the PSM, Neuhausen suggests different strategies for design improvements for the production process and product components (see Figure 6.10):

- **Change the allocation of production process to production station:** The Aim here is to group production processes with similar process parameter variations and frequency of change into production stations. This will reduce the number of stations which require changing over.

- **Integration of production stations:** The aim is to combine or integrate two production stations when both have the same dependency on product specific process characteristics. This reduces the number of stations which require changing over.

- **Differentiation of production stations:** The aim here is to divide a production station such that the resulting new production stations are dependent on different product specific process characteristics. This can be beneficial when frequency of change differs between product specific process characteristics of a station.

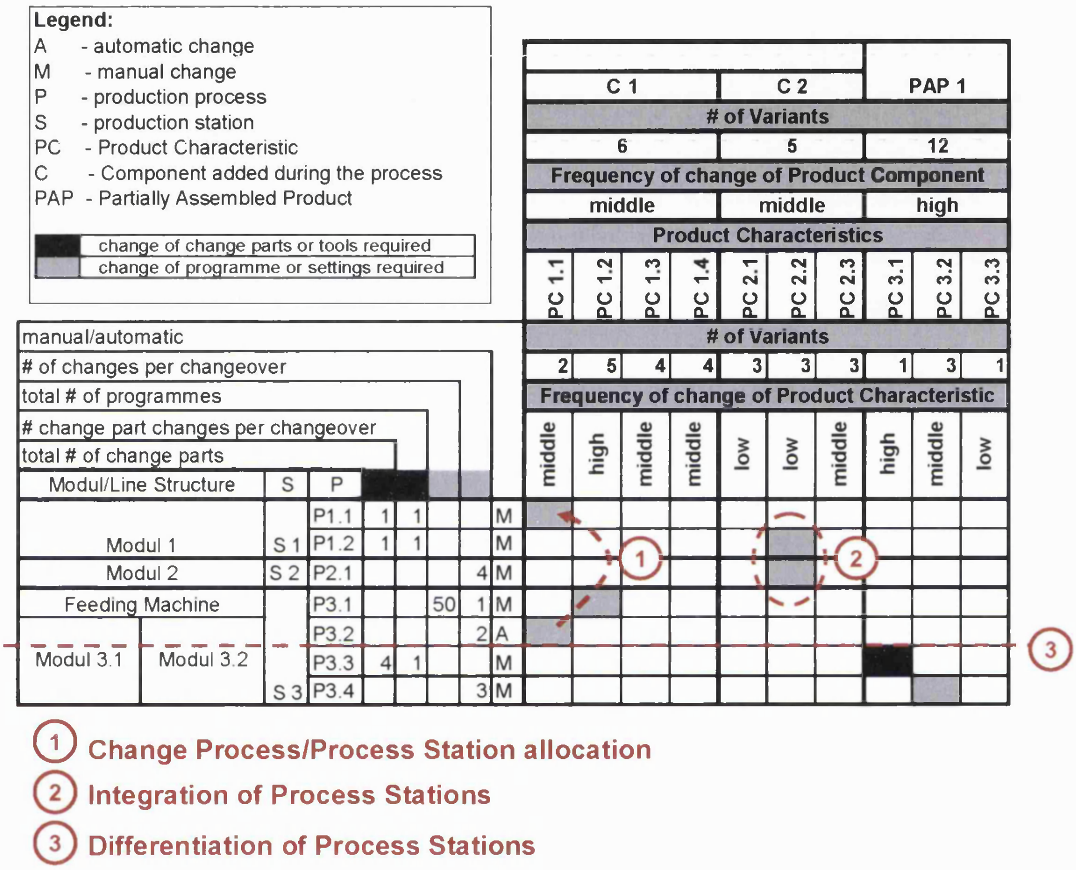

Figure 6.10 Design Improvement Strategies for modular line structure (Neuhausen, 2001)

Design for Changeability

Schuh *et al.* (2004) developed a Design for Changeability method, which allows manufacturers to determine the right degree of flexibility. Using a modular approach, they distinguish between what they call unstable and stable elements of the production system. Unstable or time variant elements are encapsulated as modules; stable or non-variant elements are encapsulated in platforms. It is argued that the changeability of a manufacturing system is determined by a limited number of change drivers. These change drivers represent the variations in product characteristics, capacity requirements, differing degrees of automation or adaptations due to changes in standards or location of production.

The production structure matrix developed by Schuh *et al.* (2004) maps change drivers to modules of the production systems and indicates which modules are affected by which change driver. This matrix can then assist in seeking improvements by changing the process configuration, by integration or separation of production elements or reduction/elimination of the influence of a change driver on a certain production element. Aim is to bundle

6.1.3 Discussion

Various approaches for the design of changeable manufacturing systems have been reviewed in the previous sections. Table 6.1 compares the different approaches according to aspects such as change drivers, design objects, improvement targets and the type of manufacturing process.

All the reviewed methodologies aim to reduce the impact of variety on the production system by isolating the impact of Change Drivers (CDs) on specific modules while aiming to uncouple other modules from the influence of the CDs. Some approaches consider only product variety as CD, other consider the whole spectrum of CDs.

Table 6.1 shows that all approaches use modularity as a key concept to achieve this. However, as is shown by the description of the design objects under consideration in the table, different approaches focus on different levels in the manufacturing systems. Some suggest strategies to improve changeability on higher levels such as the sub-factory and factory levels. Most design rules or strategies suggested, however, concern the manufacturing system or processing unit levels. Only a few approaches take the level of change parts and other settings fully into account.

Table 6.1 Comparison of design approaches for changeable manufacturing systems

		Design of an Agile Workcell (Quinn, 1996)	**Reconfigurable Manufacturing Systems** (RMSs) (Koren *et al.*, 1999)	**Design of modular production systems** (Neuhausen, 2001)	**Modular Plant Architecture** (Eversheim and Neuhausen, 2001)	**Design for Changeability** (Schuh, 2004)
Change Drivers (CDs)	Variety, Technology, Volume or Generic	Product Variety	All CDs, but with focus on generational Product Variety	Product Variety	All CDs	All CDs
Mfg. process	assy. or mfg.	light Assembly	no particular focus	focus on assy	no particular focus	no particular focus
Design objects	Factory/ Site	-	-	-	Company specific production platform which allows building of production systems using modules (production stations)	Modular approach on all levels of the production system. It is differentiated between stable elements of the production system (platform) and unstable elements (modules)
	Sub-Factory	-	-	-		
	Mfg Sys/ Lines or Line Segments	-	Platforms for modular machine tools, but also modular within line for both hardware and software. Each element designed with 5 core RMS characteristics (see separate section)	Modular approach for line segments		
	Processing Unit (production station)	Platform for modular worktable and gripper. Modularised software for easy set-up		Modular approach for production stations		
	Change Parts.	Modular gripper and worktable	Modular approach for machine tools	-	-	
Reducing the impact of CDs	Isolating Impact of CDs on	Variation adopted via software, vision system and robot	using the 5 RMS core characteristics for all modules	line segments and stations	line segments and stations	across all levels of the production system
	Uncoupling from influence of CDs	belt feeder to reduce impact of part shape and size changes	using the 5 RMS core characteristics for all modules	line segments and stations	line segments and stations	modules across all levels of the production system
Improving of trans-formation processes	Type of activities	exchange of belt for exceptional part shapes, gripper exchange, software programming	Using the modular design it is aimed to restrict transformation activities to assembly/disassembl y of modules.	Differentiation between tool change and other settings. Consideration of number of variants and frequency of change and	-	-
	Effort/time required	No evaluation of effort or time	No evaluation of effort or time	No evaluation of effort or time	-	-
	Accessibility	-	-	-	-	-

As described above the aim of all these approaches is to enable manufacturing equipment to better react to changes in CDs. There are two aspects which need to be considered when seeking to do so. First, there is usually a range of states a CD can assume. The main aim, when designing good changeable manufacturing equipment, must be the ability to adapt to as many of these states as possible. This is similar to the range flexibility in flexible manufacturing (see Chapter 2). Second, the time required to transform the manufacturing system from one state to another can be critical for the cost-effective operation of the system (see Chapter 2, response flexibility). In particular, this is the case when changes occur very frequently as is often the case for changeovers between products of a product family. The design methodologies which have been reviewed in the previous sections are all aiming to improve both aspects. Although a variety of different design principles, rules and strategies have been proposed, the reviewed approaches effectively aim to increase the changeability by seeking design which satisfy the independence axiom, the first axiom of Axiomatic Design (Eversheim and Neuhausen, 2001, Suh, 2001). However, even when considering the same functional requirements two designers could come up with a design which satisfies this axiom (Suh, 2001). It is likely that one of these designs is better and a means is required to identify this design. For this purpose Axiomatic Design relies on the second axiom (information axiom), which can be seen "as a quantitative measure of the merits of a given design" (Suh, 2001). However, regarding the methodologies reviewed above, surprisingly little thought has been given to consider the effort and time required for the transformation processes between different states of the manufacturing system. Although the methodology developed by the author is not based on Axiomatic Design, it is the aim of the current thesis to address the gap identified by providing measures to evaluate changeover performance during the equipment design phase (see Chapter 7).

There are a variety of different activities which might be required as part of these transformation processes; some of which also occur in different engineering domains and are being addressed by specific engineering design methodologies which have been proposed in the literature. An example for this is the Design for Assembly methodology developed by Boothroyd *et al.* (1994). This chapter continues with a discussion of such relevant design methodologies which are aiming to improve artefact related activities, such as assembly and disassembly.

6.2 *Improving or eliminating design artefact related activities*

A variety of approaches have been proposed in literature, which seek to improve activities related to the design artifact. By far the most prominent example for such a technique is Design for Assembly which aims to reduce the effort required to assemble a product. This section reviews such 'Design for X' methodologies relevant to changeover activitity.

6.2.1 Design for X Methodologies related to Changeover Activity

Design for X (DFX) is an umbrella term for many design philosophies and methodologies, which try to raise the designer's awareness of a certain product life-cycle value or characteristic represented by "x" (Huang, 1996). The need for such philosophies was identified as engineers became increasingly aware of a lack of appropriate detailed knowledge in important product life-cycle areas. Design for X methodologies can be seen as tools to analyse design proposals or existing designs for their suitability for certain life-cycle aspects. Manufacturability and assemblability were among the first life-cycle values to have been considered since they were highly apparent cost reduction drivers. In particular these tools bring designers and manufacturing experts together and address, typically because of education system shortcomings, lack of manufacturing expertise among designers (Benhabib, 2003).

Similarly, following the example of DFA and DFM, other DFX methodologies have been proposed to consider life-cycle values, assessing parameters like quality, maintainability, reliability, safety regulations and environmental issues earlier in the design process (Huang, 1996, Reik et al., 2004).

As described above, DFX methods are methods, sometimes embedded into formal tools, to evaluate design concepts or detailed designs and as such provide measures for the cost, quality and regulatory conformity of a certain aspect of a product's life-cycle (Reik et al., 2004). As such they provide a benchmarking tool to compare the possible relative benefits of different design solutions.

The benefit of DFX tools, which also require the involvement of functional experts, is improved performance of products and related processes. DFX methodologies do not necessarily reduce the extent of design decisions, but they help to make them earlier. Substantial cost and development time savings can potentially be made as changes are easier to make the earlier they are provoked (Huang, 1996).

The most prominent DFX methodologies are Design for Assembly (DFA) and Design for Manufacture (DFM). DFA provides methods to evaluate assemblability, assembly times and costs of a product (Boothroyd et al., 1994, Whitney, 2004). DFM attempts to help the designer to increase the manufacturability and to provide accurate manufacturing costs for a product and its components. To help this process complex cost models have been developed for different manufacturing processes and their process parameters (Swift and Booker, 1997, Boothroyd et al., 1994).

6.2.2 Design for Assembly (DFA)

Assembling is often seen as a process, which does not really add any value to the final product. Thus, reducing the amount of assembly tasks or simplifying them is very positive for companies (Boothroyd et al., 1994, Swift and Booker, 1997). A more efficient assembly process results in reduce cost and better profit margins. In addition, reduced assembly times offer reduced lead-times, which in turn can be an important advantage for the company's positioning in the market.

The aim of Design for Assembly (DFA) is to make the designers aware of what consequences their design decisions have on the product assembly, the assembly process and the costs of a product. The main part of the DFA philosophy is to reduce the amount of assembly tasks by reducing the number of parts. Parts can be eliminated by integrating them into others.

DFA Methodologies like the one proposed by Boothroyd *et al.*, identify unnecessary parts by asking the following three questions for every component:

1. Does the part move relative to other parts during the operation?

2. Must the part be of a different material and why?
3. Would a part prevent assembling other parts, if it were to be combined with a neighbouring part?

The following design rules are element of DFA as proposed by Andreasen *et al.* (1983) and simplified by Boothroyd *et al.* (1994):

1. Reduce Part Count and Part Types
2. Strive to Eliminate Adjustments
3. Design Parts to be Self Locating and Aligning
4. Consider Access and Visibility for each Operation
5. Consider the Ease of Handling of Parts from Bulk
6. Eliminate the Need for Reorientation during Assembly
7. Maximize Part Symmetry or Emphasize Asymmetry

It can be seen that DFA does not only reduce the part count, it also provides help in easing assembly for parts (Rules 2-7), which cannot be eliminated. Thus, helping to avoid parts, which require several directions of assembly and avoiding parts, which can be accidentally assembled wrongly (for example by using Poka Yoke techniques (Shingo, 1986)).

Another big problem of assembly, which is addressed by DFA, is the supply of parts to the production line. Handled by the rules 5 and 6 it is assured that parts are supplied in the right orientation and are designed such that they are not able to tangle and nest with other parts.

Computer-aided DFA tools have been developed and are now widely used, which help to decide between product design alternatives. In general the approach of these tools is to connect form and other features of parts with estimated assembly times using empirical data (Benhabib, 2003). Time penalties are given for every task, which differs from a simple downwards insertion. Further penalties are given if the assembly task involves heavy or large parts. The assembly and penalty times are not absolute values and are only used to relatively compare different assembly tasks. An assemblability index provides guidance of the quality of the design for assembly. Depending on this index it can be decided whether a redesign has to be carried out. The most popular DFA tools are the Boothroyd & Dewhurst DFMA software (Boothroyd *et al.*, 1994), the LUCAS DFA (Dalgleish *et al.*, 2000) and the HITACHI AEM (Assembly Evaluation Method) (Miyakawa and Ohashi, 1986). A flowchart of the LUCAS DFA process is shown in Figure 6.11.

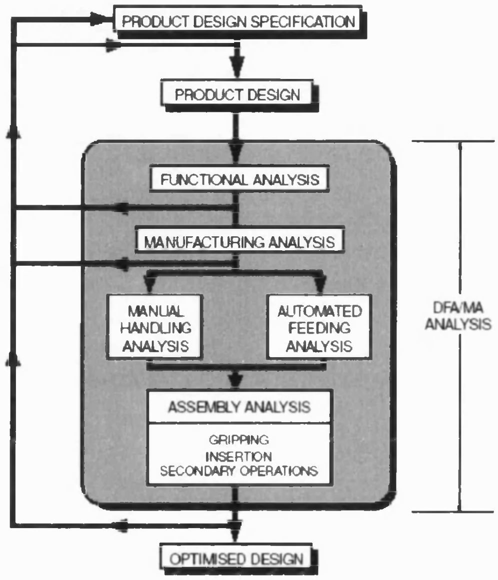

Figure 6.11 The Lucas DFA Flowchart (Dalgleish et al., 2000)

Current research is looking into automated assembly planning. Gottipolu and Ghosh (1995) identified 5 major aspects which have to be taken into account:

- Component geometry and topology representation
- Identification of precedence relationships
- Generation of feasible assembly sequences
- Assembly plan representation

- Assembly plan evaluation

One of the main problems in DFA is the amount of detailed information about the product necessary to successfully apply the methodology. Hence, DFA is frequently only applied relatively late in the New Product Introduction (NPI) Process, during the detailed design stage. Stone *et al.* (2004) developed a method called conceptual DFA using the functional basis and the method of module heuristics. The advantage of conceptual DFA is that it can be integrated in the design process at the conceptual stage of the design process. The minimum amount of modules or parts necessary to fulfil all product functions can be determined by using the functional description. Stone *et al.* (Stone et al., 2004) claim that the modular, functional description of a product helps the designer to combine the right functions into one module without introducing restrictions to the designer's creativity.

6.2.3 Design for Ergonomics

The majority of changeover activities are not automated and are undertaken by human operators or setters. Design for ergonomics deals with this human-machine interface. The three main aspects which have to be considered when designing man-machine interfaces are (Pahl and Beitz, 1996):

- Biomechanical Issues
- Physiological Issues
- Psychological Issues

Among other issues, these aspects cover limits of body movement and forces, and impact of operation on muscles fatigue and relaxation. Also controls and displays have to be designed that readings can not be misinterpreted. In terms of setting a machine this means that the response to a change in a process control variable should be obvious (Pahl and Beitz, 1996).

6.2.4 Design for Maintenance

Design for Maintenance or Design for Service (DFS) (Dewhurst, 1993) is looking into how subassemblies can be exchanged as quickly and easily as possible. Depending on the relative likelihood of failure of a certain component or subassembly more effort into improving maintainability, mainly disassemblability and assemblability, of this component is justified. Hao et al. describe how a maintainability analysis can be integrated into AutoCAD (Hao et al., 2002). Pahl *et al.* (Pahl and Beitz, 1996) describe the general goal of Design for Maintenance as a system which has complete freedom of service by designing all components with identical life, reliability and safety. If this can not be achieved service and inspection measures must be introduced.

6.3 Discussion and general requirements for a Design for Changeability Methodology

The previous sections have reviewed relevant design approaches. They have been grouped into two fields. Those methodologies which aim to reduce the impact of CDs (and more specifically product variety) and those which seek to improve artefact related activities. Section 6.1.3 provides initial discussions of specific methodologies for changeable manufacturing systems. The aim of the following sections is to give an overall critique in the light of the review on changeable manufacturing systems (Chapter 2), changeover improvement (Chapter 3) and design methodologies (earlier in this chapter).

Based on this discussion, requirements for the development of a Design for Changeover (DFC) methodology can be identified. These are described in the following sections.

6.3.1 Design for Changeover Contribution

Earlier discussions have suggested that one of the main gaps of current approaches is the lack of appropriate measures for the evaluation of changeability. Regarding the changeover activities which need to be considered, an analysis of the literature and discussion with practitioners and experts in the changeover field has shown that a DFC methodology has to incorporate the following:

- Assembly and disassembly tasks are major parts of almost every changeover and thus DFA and Design for Disassembly need to be taken into account when designing equipment with good changeover capabilities. However, different criteria apply, depending whether change elements are necessary or not. Also, a modular approach is necessary, since not every part is individually assembled or disassembled. Modules can be seen on all levels of production elements. In addition to Schuh's (2004) approach product commodities and other change elements must be considered.

- Adjustment can not always be avoided in particular when there is material and process variability. Guidance need to be given regarding for example possible adjustment mechanisms and techniques and their required precision.
- The majority of changeover activities are not automated and are undertaken by human operators or setters. Ergonomic equipment and change element design can ease changeover activity.
- Metrics specific to changeover to evaluate different designs must be developed including time, cost and quality of changeovers caused during all phases, including run-down, set-up and run-up.

6.3.2 General Requirements for a Design for Changeover Methodology

General requirements for the development of a Design for Changeover methodology can be deducted from the gaps identified in the literature in Chapter 4 and in the previous sections of this chapter[3]. As has been discussed a design methodology needs to provide systematic and structured design guidance, but also needs to provide means by which the merits of a particular design under consideration can be evaluated. For the systematic approach a changeover performance modelling system for manufacturing system designs is required. Design guidance and evaluation techniques can then be formulated on the basis of this model.

Thus, the requirements for a DFC methodology can be grouped into the requirements for a changeover performance model, the requirements for appropriate design guidance and

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[3] The requirements as they are discussed in this section concern the Design for Changeover methodology itself. The required conditions for a successful application of such a DFC methodology are subject of Chapter 5.

evaluation measures. The following general requirements for a DFC methodology have been identified:

Models required:

A generic model is needed which has the ability to describe changes occurring to a manufacturing system during a transformation process and how they are put into place. The model must be able to describe:

- the elements (or modules) and settings of the considered manufacturing system or equipment which change. The author will refer to these elements as change elements.
- the changes these elements have to undergo and the required activities
- the time and effort required for the individual activities

An integrated model is needed which is able to describe the relationships between product variety and the elements of change of the manufacturing hardware. The model must describe:

- the influence product characteristics have on change elements
- the influence of change elements on other change elements of the manufacturing system

Design guidance:

It has been identified in Chapter 5 that there are two main design artefacts when seeking to improve changeover performance using design-led methods, namely the products and the process. The review in the previous sections suggest the following general strategies which need to be addressed in these areas in order to achieve good changeover performance:

- **Product Design:**
  - Isolation of customer requirements for product variety on certain elements of the product
  - Reduce interdependency between customer perceived product variety and production hardware
- **Process Design:**
  - Isolation of the influence of product variation on certain change elements of the production hardware
  - Reduce interdependency between change elements of the production equipment and changes in CDs (These include for example customer perceived variety, but also variety introduced through for example raw material variations)
  - Reduce interdependencies between individual production change elements
  - Reduce the effort and the time required to change those change elements of the production equipment which are affected by a change in a CD
  - Optimise the design such that load balancing between changeover personnel can be achieved through sequencing of changeover activities

Together with the description of required models and design guidance required, measures are needed to evaluate the changeoverability of concepts for manufacturing systems. It is noted that other criteria which need to be fulfilled for a concept to be selected such as cost and time also apply. Trading-off of these different criteria is part of concept selection in engineering design (see for example (Pahl and Beitz, 1996)). These other criteria need to be taken into account in a DFC methodology, but are not part of the list of requirements regarding the measure for changeover performance below.

Evaluation methods to support concept selection in Design for Changeover:

- **Product Design**
    - Measures for the degree of interdependencies between customer perceived variety and product elements
    - Measures for the degree of coupling between product elements affected by product variety
- **Process Design**
    - Measures for the degree of interdependency between product variety and production change elements
    - Measures for the degree of coupling between individual production change elements affected by product variety
    - Measures for the effort and time required to change production elements affected by product variety
    - Measures for the overall time and effort required for a changeover including optimised order of activities and work balancing between multiple changeover personnel

6.3.3 The scope of the DFC methodology developed in this thesis

The aim of a Design for Changeover (DFC) methodology is to take changeover requirements into consideration during the design of process equipment. The objective is to supply designers with design rules and guidelines, but also with design analysis techniques early in the equipment and product design process. It must also aim to provide intelligent design support to enable tools, tool holder, work holder, fixtures, etc. and their associated connections and fittings within the manufacturing equipment to be quickly and precisely adapted to a new product.

Thus, a DFC methodology is aimed at optimising the changeoverability of manufacturing systems by means of re-designing the interfaces between the product and the process domain, but also the interface between the process and the human operator in case of manual changeover activities. The previous sections have developed the general requirements for a DFC methodology and gaps in literature. The scope of the work presented in this thesis based on these identified gaps is presented in Figure 6.12 and is compared with how other design methodologies reviewed earlier in this chapter satisfy the requirements.

As can be seen in Figure 6.12 the approach presented in this thesis is novel as it addresses the gaps of modelling and evaluating changeover activities. Figure 6.12 also shows that the work presented in this thesis is not aiming at addressing two aspects of the requirements as discussed above, namely the product and the load balancing and sequencing of operations. Both aspects are research areas in their on right. However, the author believes that to address these aspects appropriately both require that first of all an approach is developed with which the changeover processes of manufacturing equipment can be modelled and evaluated. This is one of the aims of the work presented in this thesis.

			Axiomatic Design (Suh, 2001)	Design for Variety (Martin, 2000)	Design of an Agile Workcell (Quinn, 1996)	Modular Production Systems (Neuhausen, 2001)	Modular Plant Architecture (Eversheim et al., 2001)	Design for Changeability (Schuh, 2004)	The author's Work
Model	Process	Change elements or modules (CEs)				❆	❆	❆	❆
		Changes CEs undergo and required activities							❆
		Time and effort of the individual activities							❆
Design Guidance	Product	Isolation of Influence of Customer Requirements (CRs)	❆	❆					
		Reduction of interdependencies between product components	❆	❆					
	Process	Isolation of influence of product variety on CEs	❆		❆	❆	❆	❆	❆
		Reduction of interdependencies between product variety and CEs			❆	❆	❆	❆	❆
		Reduction of interdependencies between CEs	❆						❆
		Reduction of effort and time required to change CEs			❆				❆
		Optimisation of design for load balancing and sequencing of activities							
Evaluation	Product	Interdependencies between CRs and product elements	❆	❆	❆				
		Degree of coupling between product elements affected by product variety	❆	❆	❆				
	Process	Influence of product variety on CEs							❆
		Degree of coupling between CEs affected by product variety							
		Effort and time required for changeover activities							❆
		Overall time and effort required for a changeover							❆

Figure 6.12 The scope of the DFC methodology developed in this thesis in regards to the requirements developed

The DFC methodology presented in this thesis is aimed in particular to assist the original equipment manufacturer (OEM) to develop new manufacturing equipment. Equally, the usefulness of the proposed methodology for equipment specifiers, equipment integrators and end-users as part of retrospective improvement initiatives is also recognised.

Thus, there are two main areas where a DFC methodology might be employed:

- New Equipment Design and Development
- Retrospective Equipment Redesign

Although it is proposed that the methodology can be applied similarly in both use cases, there are slightly differing objectives regarding specific targets for different aspects of flexibility. An end-user for example is generally interested in a high changeover performance for a specific product range (response flexibility), where the OEM often prioritises the adaptability of the developed manufacturing equipment to suit different customers and product ranges (range flexibility).

A further difference is the cost effectiveness of implementing improvement ideas. Typically, it is more difficult to justify more substantial changes to manufacturing equipment in a retrospective equipment redesign exercise.

The following chapters will describe the development of a DFC methodology based on the scope and the requirements discussed in this chapter.

7 A Design for Changeover Methodology

The previous chapters have identified the need for good changeover performance. Different ways to improve changeover performance of manufacturing systems have been discussed, in particular the design of the manufacturing equipment. Chapter 6 has developed requirements for a Design for Changeover methodology and has identified gaps within currently available approaches for the design of changeable manufacturing equipment. The key gaps which have been identified are the lack of modelling and evaluation techniques for changeover performance and the lack of a method which provides structured guidance for equipment designers. It is the aim of this chapter to address these shortcomings of available alternative approaches. The chapter begins with the description of the basic concepts and terms used within the DFC methodology and the techniques used to analyse changeover capabilities of manufacturing equipment. The chapter continues with the description of the relationships which can be identified between the different basic concepts. The chapter concludes with the description of a 9-step methodology developed by the author.

7.1 Analysis of Changeover Capabilities

Analysis of the changeover capability of manufacturing equipment is fundamental to a successful DFC methodology. This section defines basic entities associated with changeover processes, namely **change drivers**, **change elements** and **changeover activities**.

7.1.1 The Changeover Process

The changeover process is often only defined from an operational point of view in terms of time elapsed from last good part to first good part (Trevino et al., 1993, Sekine and Arai, 1992). McIntosh *et al.* define changeover time as the time elapsed from the point when full production of product A ceases to the point where manufacture of product B reached set output and quality rates (McIntosh *et al.*, 2001). Figure 7.1 shows a generic behaviour of the line output during a changeover, showing greater manufacturing losses can be prevalent over and above those which a simple good-part-to-good-part analysis embodies.

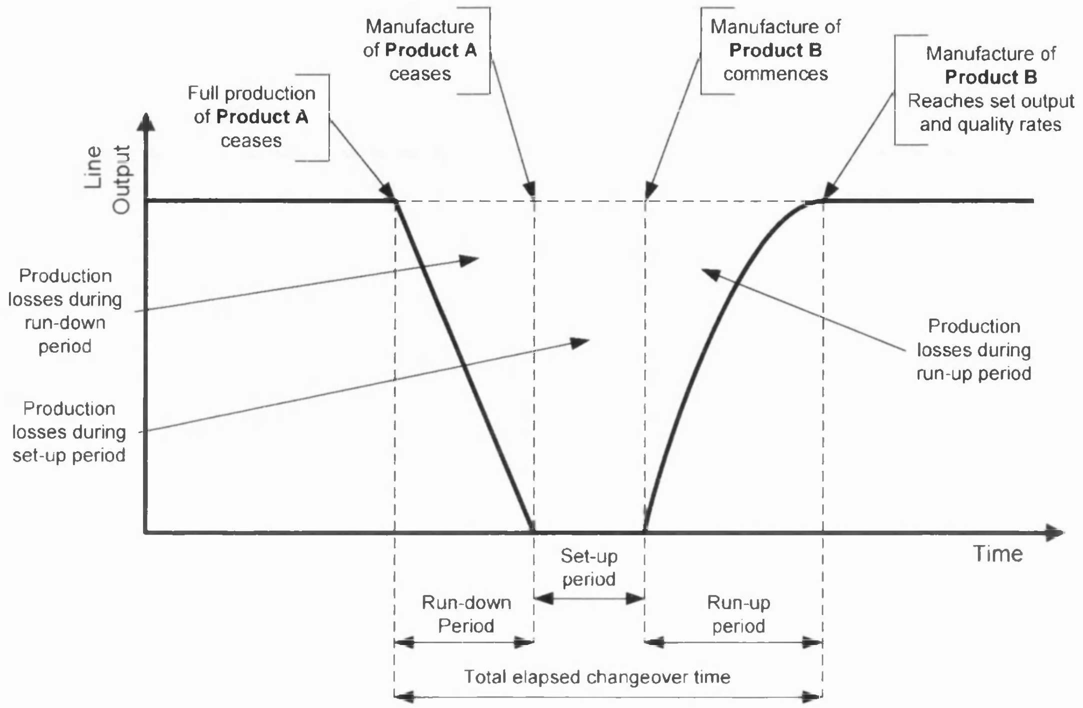


Figure 7.1 Representative line output during changeover (McIntosh *et al.*, 2001)

Changeover activities in this sense might occur during any of the three changeover phases (run-down, set-up or run-up (McIntosh *et al.*, 2001)), but can also occur before or after, for example as part of the preparation for a changeover or for the tidying up of tools once production is fully reinstated.

The first aspect is to identify what can be thought of as required changeover activities (RCAs) as opposed to the non-optimised activities which can actually occur. It will be seen that these RCAs are determined by what will be referred to as change elements and their design. Their position in the overall picture is illustrated by the enhanced 4P diagram in Figure 7.2. In turn the sum of these RCAs determines the *minimum* total effort required for a changeover on a given manufacturing system.

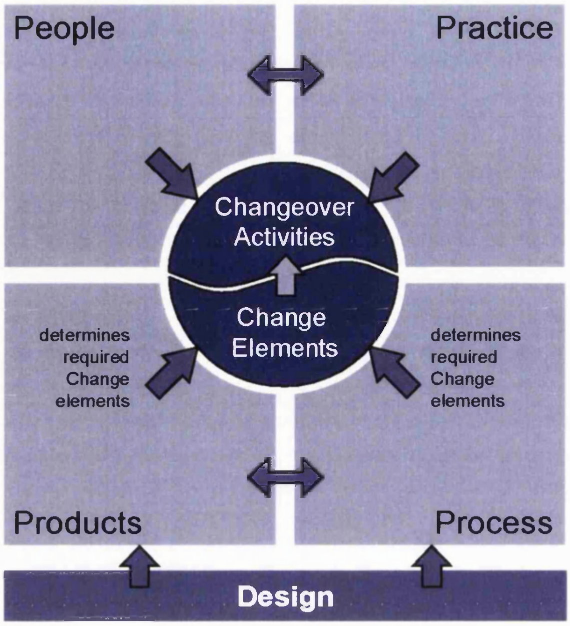


Figure 7.2 Enhanced 4P diagram: Elements of a changeover

7.1.2 Change Drivers - the Need for Product Changeover

Manufacturing systems are often required to adapt due to changing market conditions or a changing environment. In the literature these drivers are sometimes called change drivers (St. John *et al.*, 2001, Schuh *et al.*, 2004).

One of the requirements of the Design for Changeover research is to increase the understanding of elements involved as well as the activities occurring during changeovers, particularly those driven by product variation, the most frequent change driver for most manufacturing companies.

The purpose of a product changeover is to adapt a manufacturing system such that the output of the system is changed to an alternative product at a set quality and output rate. A changeover driven by product variation can thus be described by variations in product parameters (such as dimension, colour, material and quality) and output rate (Mileham *et al.*, 2004, Schuh *et al.*, 2004). Being able to adapt to possible changes in these drivers is the key requirement of a Design for Changeover (DFC) methodology.

All activities which need to occur during a specific type of changeover are driven by certain change drivers. Dependent upon the specific change drivers initiating a certain changeover, and relative to the status of the manufacturing system prior to commencement, changeover times often vary considerably. In one case, for example, a changeover might only involve one minor amendment to just one machine of a manufacturing line, whereas in another case all line stations might require significant adaptation.

Identifying all change drivers is important in developing an in-depth understanding of the flexibility required of a manufacturing system. Before a system with a high degree of flexibility and responsiveness can be designed, the product range, the possible variations in quality and output rate must be understood. Also, future market demands and requirements need to be considered.

The concepts presented in this thesis are concentrating on change driven by required changes in product parameters, since this is the most common reason for changeover activity to occur (Table 7.1 shows some example product parameter change drivers).

Table 7.1 Examples of product parameter Change Drivers (all based on actual examples)

Changes in product parameters	Product Parameter Values
Change in component shape (for example in the case of a forged part)	cam shaft 1 cam shaft 2
Change in test object's dimension (vibration test unit for electronic devices)	100x40x30 100x30x20
Change in wire diameter (shopping trolley case study)	0.5 mm 0.7 mm 2.0 mm
Added/removed feature such as an optional cross hole in a journal bearings	No cross holes 4 cross holes 6 cross holes

7.1.3 Equipment Platform, Change Elements, Changeover Activities and Resources

The Design for Changeover methodology as developed in this chapter models the time and effort required for a changeover using **changeover activities** and required **resources**. The activities and resources required to perform a certain type of changeover are mainly defined by the properties of certain **change elements** and their interaction with the unchanged remainder of the equipment hardware, namely the **equipment platform**. These key determinants of overall changeover performance are now assessed in more detail.

Equipment and Product Change Elements

For the purpose of this work the author has adopted a definition of the changeover process which varies from the operational definition of a changeover from Trevino *et al.* (Trevino et al., 1993) and McIntosh *et al.* (McIntosh et al., 2001) as:

> *A set of activities required to manipulate certain elements to correctly set and/or adjust manufacturing equipment in order to produce the new product at the desired quality and at the desired output rate.*

The author will refer to the elements in this definition as **change elements**, and to the associated activities for the manipulation of these change elements as **changeover activities**.

Using the above definition of a changeover process, it is possible to categorise change elements as:

- **Equipment Change Elements (ECEs):** Parts/Subassemblies of manufacturing hardware affected by changeover activity
- **Product Change Elements (PCEs):** Raw material, WIP/semi-finished products and finished products

Typically, ECEs are conceptually straightforward, whereas PCEs are more wide ranging and subtle. Thus PCEs can be either raw materials, work-in-progress or finished products which are manipulated for changeover purposes. This is the case, for example, where raw material needs to be put in place on or around the machine. A specific example would be the clamping of raw material on the bed of a CNC machine in a one-off manufacturing environment.

In cases where adjustment is necessary for a CE there is also often a need for checking and/or controlling of the adjustment. This might for example involve a test run of the process. The products, work-in-progress or raw materials which are handled during such a test run are not considered PCEs in the context of this paper.

The Scope of Equipment Change Elements (ECEs) and the equipment platform

It is possible and useful to illustrate these concepts diagrammatically as shown in Figure 7.3. The figure illustrates the concepts of the equipment platform and equipment change elements (ECEs). The concepts are formally defined below.

Not all elements of the process hardware are ECEs. With reference to work by Schuh *et al.* (2004), ECEs can be identified using a modular approach as illustrated in Figure 7.3:

Machine system components which are not affected by any changeover comprise the **Equipment Platform**.

Manufacturing equipment components which experience some form of change during a changeover are called **Equipment Change Elements** (ECEs).

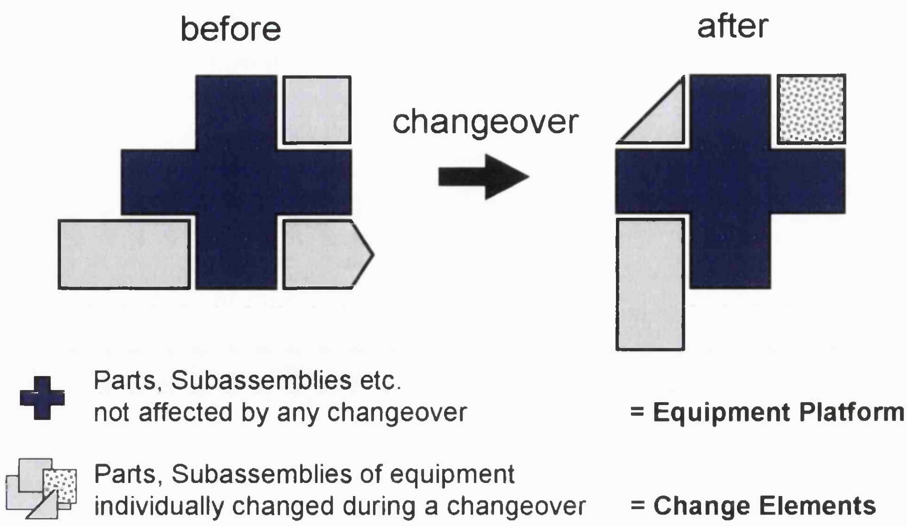


Figure 7.3 Change elements involved in changeover processes

Usually the majority of CEs can be considered as Equipment CEs (ECEs) (change parts and other parts or modules) as opposed to Product CEs (PCEs). These parts can be individual parts, or can be modules or sub-assemblies which remain completely unaltered as a physical entity during the changeover process (similar to what Perremans defines as an 'ensemble' (Perremans, 1996)). As described by Schuh *et al.* (2004) the concept of a change element can be further expanded to include whole machines or stations. If applicable, ECEs can even be extended to include complete lines or defined sections of a larger manufacturing facility.

7.1.4 Changeover Activities

Manipulation of a change element is achieved by a series of individual changeover activities. The different types of changeover activities which can be associated with change elements are listed in Table 7.2.

In addition to regular disassembly and assembly, a majority of changeover activity can often comprise setting and adjustment (Shingo, 1985, Sekine and Arai, 1992), where right-first-time setting cannot be guaranteed because of insufficient repeatability and accuracy. Research has indicated that this arises particularly for reasons of variation; in the product, its materials or in the process itself (McIntosh et al., 2001). Although there are some cases where product variety cannot be avoided, for example when processing natural food ingredients, process and product designers should generally aim to eliminate this variety.

With reference also to Figure 7.4, Table 7.2 explains the various activities with which the manipulation of the different types of change elements (CEs) during a changeover can be described:

Table 7.2 Activities that can be associated to CEs

Activity	Description
Disassembly (Disass)	Change Element not required anymore or to provide access
Assembly (Ass)	Change Element was not on machine, but is now required
Setting (Set)	▪ Change in Location/Orientation: The location or orientation of the change element needs to be set. ▪ Change in state: Change in the state of the change element can include changes in energy content (such as temperature, velocity, pressure, form for smart materials) or working motions (such as direction and path). Purging or cleaning of change elements also falls into this category.
Adjustment (Adj)	Resetting or Repositioning is necessary. Also includes the possible disassembly and assembly of other change elements in order to make resetting possible.
Checking & controlling (CC)	Set and/or adjusted values need to be checked & controlled. Includes test runs, quality checks and measurements.

The influence of the changeover activities described above on Change Elements (CEs) is illustrated in Figure 7.4.

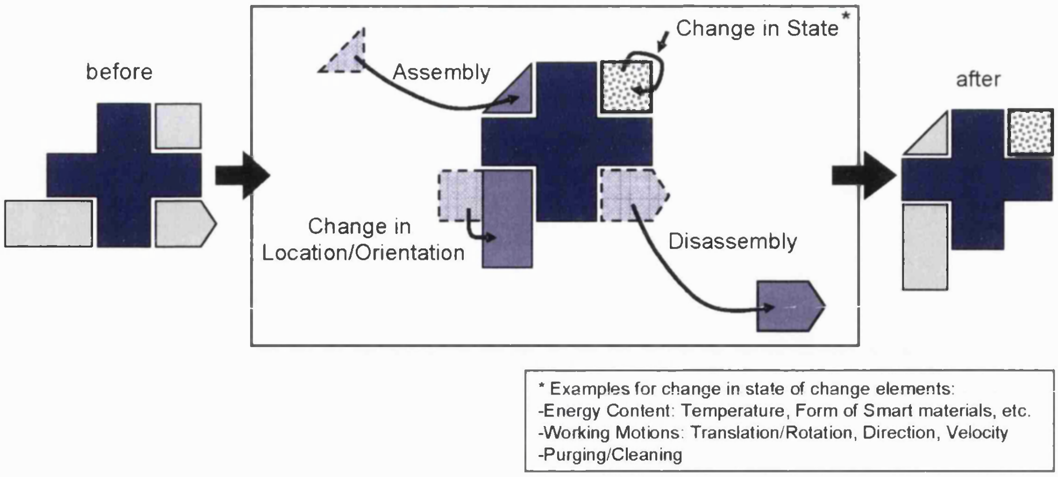


Figure 7.4 Possible changes to Change Elements (CEs) during a changeover

Resources

The idea of resources has been previously mentioned and is another important consideration. In the context of the DFC Methodology **Resources** are items such as hand tools, power tools, gantry cranes and measuring devices which are required to or assist in manipulating CEs. Resources are associated with certain changeover activities which in turn are associated to CEs. In this regard resources can have a strong influence on the effort and time required for the manipulation of CEs.

7.1.5 Classifying Equipment Change Elements (ECEs)

The underlying philosophies of DFA (Design for Assembly) are considered by the author to be potentially applicable in a changeover context. Namely, DFA seeks to determine whether a part is necessary or unnecessary and therefore whether any possibility for improvement or removal exists. This rationale can similarly be adopted in terms of considering necessary and unnecessary equipment change elements (ECEs).

Necessary ECEs can easily be identified by asking:

"Does this change element have any functional contact in any way with the product - at any time throughout the entire manufacturing process?"

A functional contact between the change element and the product exists if there is an interface (Pahl and Beitz, 1996) (see following sub-section) between them, that is, if there is a direct interaction between the ECE and the product. Change elements for which the answer is yes are what Whitney (Whitney, 2004) classifies as main function carriers and include what Rogers *et al.* (Rogers and Bottaci 1997) define as modular tooling and jigging. In the context of DFC, the author defines these CEs as functional Equipment CEs (F-ECEs) and they are considered to be necessary CEs. Typically all other elements are candidates for elimination (which is one very important way for identifying improvement opportunities; further mechanisms are presented later in this chapter) and are considered to be unnecessary CEs.

The concept of the Product and ECE interface

In making such an assessment, an understanding of what is meant by an interface needs to be in place. A general definition of interfaces (Pahl and Beitz, 1996) categorises interactions between two interfacing elements as:

- Spatial: Shape, location or orientation of the elements define the interface
- Energy flow: Energy is transmitted from one element to the other
- Information flow: Information is transmitted between the participating elements
- Material flow: Material is transmitted between the participating elements

This standard definition will be used in the context of this work.

A classification of Equipment Change Elements (ECEs)

Classifying further, change elements which do not have any interface with the product throughout the manufacturing process – and which therefore are not necessary equipment change elements - can be of two types:

First, the change element may be assisting necessary change elements to accommodate required changes arising from the change drivers (functional and geometric support (Whitney, 2004)). These are defined as Primary Support-ECEs (PS-ECEs). An example of this type would be shims or spacer pieces used to locate a sub-assembly.

Second, the change element might only be involved in a changeover to provide access or to secure other change elements (ergonomic support or fasteners (Whitney, 2004)). These are defined as Secondary Support-ECEs (SS-ECEs). Examples of these could be clamping screws or safety covers.

These two situations must also be recognised and therefore together overall change elements can be categorised as shown in Table 7.3.

Table 7.3 Classification of Equipment Change Elements

Equipment Change Element (ECE) Classification		Description
Necessary ECEs	Functional Change Elements (F-ECEs)	CE interfaces with the product
Unnecessary ECEs	Primary Support CEs (PS-ECEs)	Assist other CEs in achieving a required change of their status, location or orientation (for example, shims help locating a F-ECE)
	Secondary Support CEs (SS-ECEs)	Provide access/securing to other CEs

The identification of these change elements is important for the elimination of individually manipulated change elements, similar to DFA where assembly efficiency is increased by part count reduction. The classification of ECEs as described in this section assists identifying those change elements which can potentially be eliminated by altering the manufacturing hardware without changing the product design or product mix.

The foremost aim of the DFC approach presented is to optimise changeover performance of manufacturing equipment for the manufacture of an existing or planned range of products. For that reason the focus of the methodology will be on the 3 types of Equipment Change Elements (ECEs) as classified in Table 7.3. It has been discussed previously that the majority of CEs are ECEs. For simplicity the remainder of this thesis is thus using Equipment Change Elements (ECEs) and Change Elements (CEs) as interchangeable concepts. Unless specifically mentioned, Product Change Elements (PCEs) will not be considered any further in this work.

7.2 Evaluation of Equipment Design

It will be seen that metrics to evaluate the changeover capabilities of existing or proposed equipment designs are an important aspect of a DFC methodology. The main use of these metrics will be to quantify the benefit or improvement associated with revised design proposals.

Earlier sections have shown that changeover of manufacturing equipment can be described by the change elements and the changeover activities associated with them. An approach is now proposed where changeovers are analysed using change elements and changeover activities previously described. These two analyses are referred to as the Design Efficiency Analysis (DEA) and the Changeover Activities Analysis (CAA).

The following sections provide more detailed information on these two types of analyses.

7.2.1 Design Efficiency Analysis

Based on the identification of necessary change elements, a Design Efficiency Index similar to the design efficiency of DFA methods (Swift and Booker, 1997) can be defined. The DFC Design Efficiency Index is calculated as the ratio between the number of necessary change elements and the total number of change elements:

$$I_{DE} = \frac{\text{necessary CE}}{\text{all CE}} \cdot 100\% \qquad (1)$$

The Design Efficiency Index assists focusing improvement efforts on the reduction of the change element count (here ECEs) by distinguishing between change elements which have a functional contact with the product (necessary CEs) and those without any form of contact (unnecessary CEs). However, there are frequently trade-offs between the reduction of change elements and the reduction of changeover activities (in some cases it can be beneficial to increase the number of change elements if this significantly reduces the effort involved in changing these elements). Therefore a Changeover Activity Index has additionally been developed, which attempts to assess the relative effort involved in completing a changeover.

7.2.2 Changeover Activities Analysis

It should be noted that in the early stages of a design process there is typically little detailed information available about the effort and duration of changeover activities. For this reason two strategies have been developed to analyse changeover activities. Either one or the other can be adopted. Strategy A can be used when detailed information of change elements and changeover activities is known to the designer. Strategy B requires less information and is thought to be more relevant for designers during early phases of the design of new manufacturing equipment.

Strategy A – Retrospective Time-based

The Changeover Activity Index is calculated as the time ratio of necessary changeover activity to total changeover activity:

$$(2) \qquad I_{DE} = \frac{\text{time of necessary Changeover Activities}}{\text{time of all Changeover Activities}} \cdot 100\%$$

All activity associated with change elements which have not been classified as necessary change elements are unnecessary activity. Furthermore, other criteria apply to activities associated with necessary change elements so that only disassembly, assembly and, in some cases, setting/positioning are seen as necessary activity. Any other activity is considered to be non-value added activity and its elimination should be aimed for.

Strategy B – Proactive, early design stages

In the proactive design of new equipment an accurate estimation of changeover times can be difficult. Strategy B has also been developed as an alternative way to analyse changeover activities. This approach is based on the scores given to different activities associated to a certain change element in situations where it is difficult to make any assessment of the effort necessary to complete selected changeover tasks. In such a case the scores simply indicate that a certain activity needs to be done. Alternatively, if relative efforts are assumed to be known, scores can indicate the difficulty of changeover activities.

(3) $$I_{DE} = \frac{\sum \text{scores of necessary Changeover Activities}}{\sum \text{scores of all Changeover Activities}} \cdot 100\%$$

Impact of Setting and Adjustment activities

For both cases – for strategy A and strategy B - it can be difficult to estimate the impact of any setting and adjustment activities that may be required. Therefore, a penalty mechanism is proposed for change elements with adjustment operations. Different penalty 'loads' can be applied based on operational experience and observations of actual changeovers.

It is assumed that all operations associated with the change element in need of adjustment are repeated at least twice in order to manipulate it into its final position. Since checking operations are also necessary, it is proposed that in the first instance change elements in need of adjustment are penalised by multiplying their operation times by a factor of three. In the implementation and use of the DFC methodology this can be increased in cases of difficult adjustment or where additional checking operations need to occur. The penalty factor can be further increased if settings can only be controlled by test runs of the process and scrap is produced. These will be based on domain related experiences.

7.3 DFC Analysis - Reflections and Overview

Chapter 5 has shown that the overall landscape of changeover improvement can be described by the 4Ps, **People**, **Practice**, **Products** and **Process**. Based on this, the current chapter introduces various concepts to model changeover capabilities of manufacturing equipment. These concepts are: **change drivers**, **change elements**, **changeover activities** and **resources**.

In addition two metrics for evaluating changeover capabilities are described: the Design Efficiency Index and the Changeover Activities Index. These metrics can support seeking improvement. However, their focus is on eliminating unnecessary Change Elements and Changeover Activities. In general, improvement for a particular type of changeover, that is a particular set of change drivers, can be sought by:

1. Reducing the number of CEs
2. Reduce the effort to change CEs

Techniques for reducing CE count are eliminating or reducing the influence of change drivers on the manufacturing equipment or grouping of CEs (determination of modules (Bi and Zhang, 2001)). Reducing the effort to change CEs can be achieved by techniques such as reduction of resources, separation of CEs to ease handling or using Poka-Yoke design principles (Van Goubergen and Van Landeghem, 2002).

Some possible trade-offs between these two areas of improvement have been described in this chapter. They need to be considered if improvement possibilities are evaluated.

This chapter will continue with the introduction of the comprehensive DFC methodology which has been developed based on the theoretical concepts described in the previous sections.

7.4 Relationships between Change Drivers and Change Elements

As has been described in the previous sections, an Equipment Change Element (ECE) can be categorised as **Functional ECE (F-ECE)**, **Primary Support ECE (PS-ECE)** and **Secondary Support SS-ECE)** depending on a specific change driver and its influence on this change element.

An example of these relationships is the product change on a simple stamping press. In this example the change in the product shape requires the dies to be exchanged. The two die halves are in touch with the product during the stamping process and thus are functional equipment change elements (F-ECEs). The two die halves are fastened to the press by a set of clamps. These need to be removed and replaced in order to gain access to the old die halves and to secure the new die set. The clamps therefore are secondary support-ECEs (SS-ECEs). These relationships can be mapped in a matrix as illustrated in Figure 7.5. A more complete example of such a relationship matrix is shown in the case studies presented in Chapter 8 and Chapter 10.

Change Drivers		change elements				
Product Parameters	**Variation**	**die set Shape A)**	**die set Shape B)**	**die set Shape C)**	**die set Shape D)**	die clamps
Shape	Shape A	A				C
	Shape B		A			C
	Shape C			A		C
	Shape D				A	C

A - Functional ECEs B - Prim. Support ECEs C - Sec. Support ECEs

Figure 7.5 Sample Change Driver-Change Element Relationships

7.5 The Change Driver Flow-Down

Following from work by Martin *et al.* (2002) and Whitney (2004) the author proposes a method for the analysis of equipment changeover which decomposes the changes in drivers into required changes to the change elements. A required change in one change element might then be decomposed further into changes of other change elements. These change driver flow-down relationships can best be described by a hierarchical tree structure.

The change driver flow-down relationships are illustrated in Figure 7.6 for the case of a product change and its effect on the die sets of a stamping press described above. At the top of the hierarchy is a certain change driver or a combination of change drivers. The other levels of the hierarchy are based on the three types of change elements.

The change driver flow-down relationships are determined from the information presented in Figure 7.5 and the changeover activities related to the affected change elements.

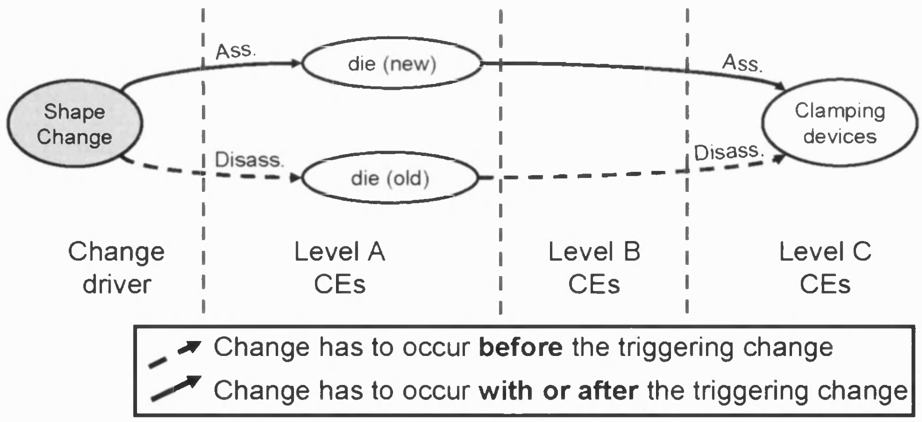


Figure 7.6 Sample illustration of a change driver flow-down tree structure

The change driver flow-down as pictured in Figure 7.6 is read in the following way:

> *A change in the product triggers a disassembly change in the old/current die set (Level A), which in turn triggers disassembly tasks for the clamping devices of the dies (Level C). The product change also triggers an assembly task for the new die set*

(Level A), which in turn requires the clamping devices to be assembled again (Level C). (In this example there is no Level B change element.)

The benefit of the hierarchical representation of Figure 7.6 is the guidance it can provide as to where to concentrate improvement effort. Improvement can be undertaken by eliminating the influence of a change driver on a change element, thus, eliminating this change element. The higher in the hierarchy this interruption takes place the greater are the potential benefits in respect of changeover performance. The reason for this is that once a change element is not influenced by a change driver (that is, the change element has been eliminated), all change elements in lower levels which are only related to this CE are also eliminated. In other words the change driver flow-down is interrupted and change elements are no longer influenced by any changes in the driver.

Alternatively, changeover performance can be improved by making changes happen more easily. Again the impact of improvement is potentially far greater if undertaken on higher levels of the change driver flow-down hierarchy - that is, concerning elements towards the left hand side of Figure 7.6. As an example for this in the case illustrated above, eliminating the need to change the dies all together would be more beneficial than just eliminating the clamping devices for them.

7.6 The Design for Changeover Methodology

The previous sections highlight the considerations associated with DFC and the underlying philosophies and concepts of the approach. The following section elaborates the overall step by step DFC methodology.

The aim of the DFC methodology is to provide assistance to OEM designers during the design and development of new manufacturing equipment. It is additionally aimed at designers concerned with improving existing manufacturing systems. The overall generic process is shown in Figure 7.7.

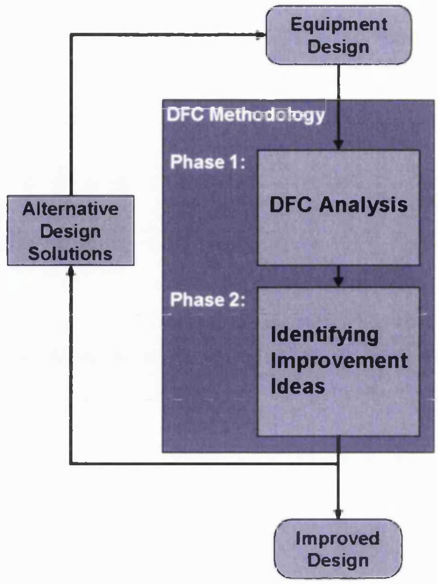


Figure 7.7 Flowchart of the Design for Changeover Process

The author proposes a 9-step DFC methodology based on the critical elements identified in the previous sections. This methodology provides guidance for designers from the modelling and evaluation of a changeover process through to identifying improvement possibilities. The methodology concludes with the selection of improvement concepts and evaluation of the improved design. An overview of the 9-step DFC Methodology is shown in Figure 7.8.

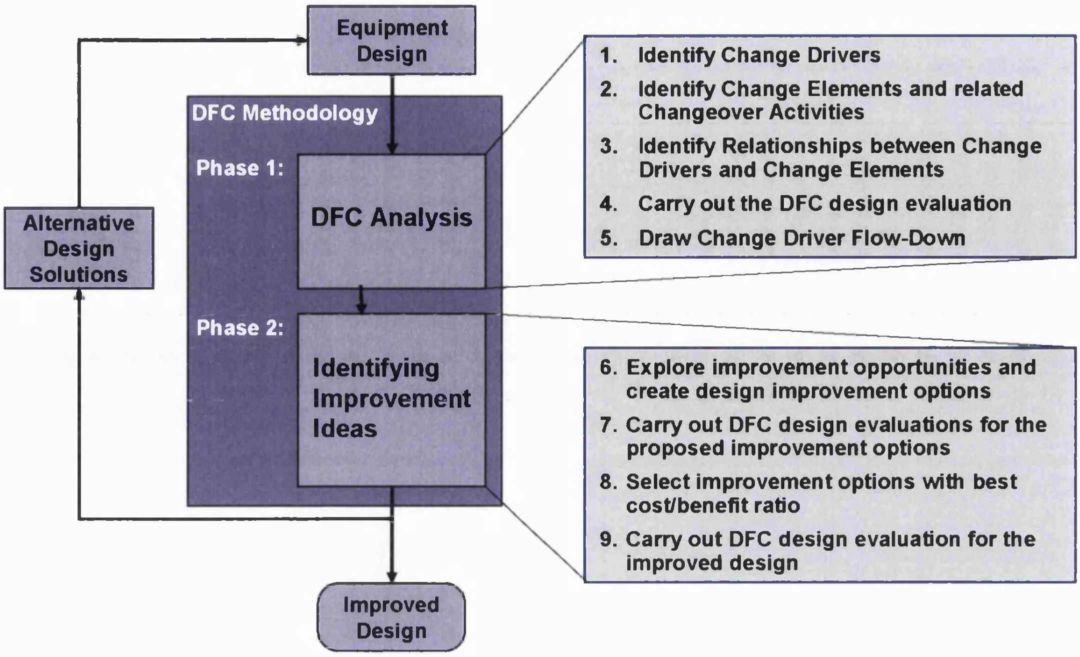


Figure 7.8 The 9-step DFC Methodology

The 9-step DFC Methodology provides a formal procedure to evaluate design improvement opportunities. The outcome inevitably is dependent on how people individually use it. However, the methodology's evaluation indices provide a means to compare different improvement options created by the user in terms of both their cost and impact.

To increase the potential outcome of the methodology, it is best performed as a group exercise, seeking input from personnel from different departments and with differing backgrounds (which is similar to best practice suggested by other DFC methodologies such as DFA (Boothroyd *et al.*, 1994)).

The author's research presented in this thesis has been informed by collaboration with manufacturing companies from different sectors such as automotive, commodities, health care and the food industry. The collaboration has taken the form of designing and analysing various operations at various stages of the methodology. During these collaborations various manufacturing processes, such as assembly, joining, forming, stamping, conveying, machining and printing have subsequently been analysed. The concepts and techniques used during the DFC methodology presented in this chapter are independent of the industry sector and the type of manufacturing process.

The following section describes each of the steps. Case studies utilising this approach are presented in Chapter 8. The steps are conveniently split into two phases, namely *Analysis and Presenting the Issues* (step 1-5) and *Making Improvement* (6-9) as shown in Figure 7.7.

7.6.1 Phase 1 - Analysing and presenting the issues (Step 1-5)

Step 1 - Identify change drivers

As noted in the earlier parts of the chapter, there are many internal or external drivers which can force changes to equipment hardware to be made. The focus of the current work is product changeovers. Thus, changes in the product parameters are the main drivers for the changes to be made.

The drivers responsible for changes to change elements to occur during a product changeover may be determined by asking the following questions:

- Which Product Mix has to be dealt with?
- What are the differences between products?
- Which product parameters describe these differences and what are their values?

Outcome of Step 1

The outcome of this first step could for example be a list of products, a list of product parameters describing these products and a list of possible product parameter values for each product parameter.

Step 2 - Identify change elements and related changeover activities

The following questions may help identifying equipment and product change elements:

Equipment Change Elements: Which elements of the equipment are affected by changes in the change drivers? Which other elements of the process hardware need to be manipulated during a changeover? How do these CEs need to be manipulated?

Product Change Elements: Is the product, work-in-progress or raw material manipulated during the changeover? Is this manipulation part of the set-up?

Outcome of Step 2

The outcome of this step is a list of change elements (equipment and product change elements) and a list of related changeover activities for each change element.

Step 3 - Identify Relationships between Change Drivers and Change Elements

The relationships between change drivers and change elements are defined by what influence a change driver has on a change element and the required change of this CE. This part is similar to the production structure matrix proposed by Neuhausen (Neuhausen, 2001) and Schuh et al. (2004), so that relationships between change drivers and CEs can be described in a matrix form. As a part of this step Change Elements are classified as Functional ECEs (F-ECEs), Primary Support ECEs (PS-ECEs) and Secondary Support ECEs (SS-ECEs) depending on the considered Change Drivers. Figure 7.5 presents an example of such a matrix. A fuller example is shown in the case studies described in detail in Chapter 8.

Outcome of Step 3

The outcome of this step is the change driver-change element relationship matrix which shows which CEs are influenced by which change drivers and shows the classification of each CE regarding each change driver.

Step 4 - Carry out the DFC design evaluation

The DFC evaluation is carried out using the DFC Evaluation Sheet which is shown and explained in detail in the first case study covered in Chapter 8. The DFC evaluation sheet contains information about all change elements and their associated activities for a certain type of changeover, that is a specific change driver or a specific combination of change drivers.

Outcome of Step 4

The results of this step are the two indices described in the first part of this paper, the Design Efficiency Index and the Changeover Activities Index. The total number of CEs and changeover activities and the overall time or effort are also part of the results and are useful benchmarking measures.

Step 5 - Represent relationships of Step 3 in a graphical, hierarchical manner

The relationships identified in the previous steps can be illustrated in a graphical manner to increase the understanding of the equipment changeover in question and to support the identification of improvement opportunities. For this purpose the author have introduced the Change Driver Flow-Down in section 7.5. Construction of this Change Driver Flow-Down is the aim of the current step.

Outcome of Step 5

The output from this step is a Change Driver Flow-Down for each change driver or set of change drivers.

7.6.2 Phase 2 - Making Improvement (Steps 6-9)

Step 6 - Exploration for improvement opportunities and the creation of design improvement concepts

Improvement can be achieved by either eliminating CEs or by reducing the effort which is required to change a CE. The following procedure can be used to systematically explore the change driver flow-down hierarchy to identify improvement opportunities:

1. *Go to Level A in the Change Driver Flow-Down generated in Step 5*
2. *For all CEs on this level check improvement possibilities:*
    a) ***Elimination of CE** by*
        - *Eliminating influence of Change Drivers (CDs) or higher level CEs*
        - *Grouping of CEs into modules with other CE of same or higher level (limitations such as maximum weight for operators apply)*

    b) ***Reduce effort to change this CE** for example by*
        1. *Minimise securing/releasing effort*
        2. *Eliminate need for adjustment*
        3. *Provision of setting, measuring, testing and controlling devices and procedures*
        4. *Provision of power tools*
        5. *Use Poka-Yoke (foolproof design)*
        6. *Reduce weight*
        7. *Increase accessibility*
        8. *Separation of CE into modules to accommodate changes easier*

    c) ***Enable changing of CE in parallel to others***
3. *Go to next level in Change Driver Flow-Down and continue with Step 2*

Outcome of Step 6

This procedure first seeks to interrupt the change driver flow-down by eliminating change elements. If a CE can not be eliminated the procedure seeks improvement possibilities by reducing the effort to change the CE.

This step will result in a list of improvement ideas being generated by the improvement team (following the procedure described above). An example for this would be the improvement ideas listed on the left-hand side of Table 8.2 presented as part of the later case study.

Step 7 - Carry out DFC design evaluations for the proposed improvement concepts

Further to step 6, all improvement concepts can be evaluated in terms of their cost to implement and their benefit in terms of reduction of the change element count and the reduction of the time or effort involved in completing a changeover. Implementation costs can be estimated using standard cost-estimation methods. The impact on changeover performance can be evaluated by estimating the likely impact of the improvement concept on the results of Step 4. In particular the possible reduction of CEs and the reduction of changeover activities are here useful benchmarking measures.

Outcome of Step 7

Outcome of this step is a complete list of improvement ideas with evaluation results for each of the ideas (see Table 8.2 in the case study).

Step 8 - Select improvement concepts with the best cost/benefit ratio

The evaluation of improvement concepts in the previous step allows a crude cost/benefit ratio to be calculated, which can be used as the basis of concept selection. Bado (Bado, 2005) has shown that changeover performance can be directly related to its impact on the business operations using Benefit-Performance Curves calculated for the possible benefits identified by McIntosh *et al.* (2001). One example of such a curve is shown in Figure 7.9, where the potential benefits through inventory reduction are considered. The curve plots the expected cost savings over the relative reduction in changeover time.

The concepts generated in Step 6 can be plotted on the graph depending on their evaluation results in Step 7. Concepts which are selected for implementation need to be below the Benefit-Performance Curves in the graph to be economically feasible.

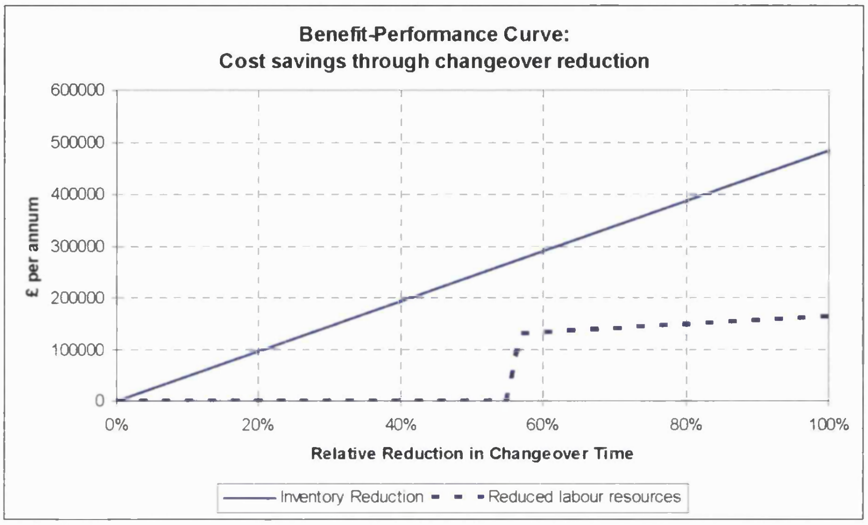


Figure 7.9 **An Example Benefit-Performance Curve from a case study regarding streamlined warehouse operations (Bado, 2005)**

Outcome of Step 8

The aim of this step is to generate a list of improvement ideas which satisfy cost and benefit criteria and are therefore selected for implementation.

Step 9 - Carry out the DFC design evaluation for the improved design

The final step of the DFC methodology is to estimate the impact of the selected improvement concepts. This step is necessary since the benefits of single improvement concepts alone are not necessarily equal to the combined benefits when undertaking a number of improvement options together, which would be the case for example if two improvement ideas are to be implemented and both affect the same changeover activity.

Outcome of Step 9

The evaluation of the improved design is carried out similar to Step 4 using the DFC Evaluation Sheet. Again, the results of this step are the two indices described in the first part of this paper, the Design Efficiency Index and the Changeover Activities Index. Also, the total number of CEs and changeover activities and the overall time or effort are useful benchmarking measures. Impact of the concepts selected for implementation can be established by comparing these results with the results of Step 4.

7.7 Conclusion

The author's 9-step methodology is the first attempt to put in place the necessary elements for a comprehensive Design for Changeover (DFC) approach. The approach has been tested on a number of different cases as part of its development and validation, some of which are described in more detail in the following chapters. Although presented as a total step by step methodology some of the critical contributions of the work are the underlying philosophy behind the approach and the identification of fundamental core parts of the changeover process, namely change drivers, equipment platform, change elements, changeover activities and resources and the change driver flow-down.

The Change Driver Flow-down is a new way to graphically illustrate required changes during a changeover that has been introduced. Besides providing a tool to understand changeover processes, the Change Driver Flow-Down is the basis for the systematic approach to identifying improvement opportunities presented in Step 6.

The methodology has been exposed to a number of industrial collaborators. This has revealed that dependent upon design stage, machine type, manufacturing process and system certain steps of the methodology are more valuable than others. Two case studies are presented in the following chapter. The case studies have been chosen to illustrate the use of all 9 steps.

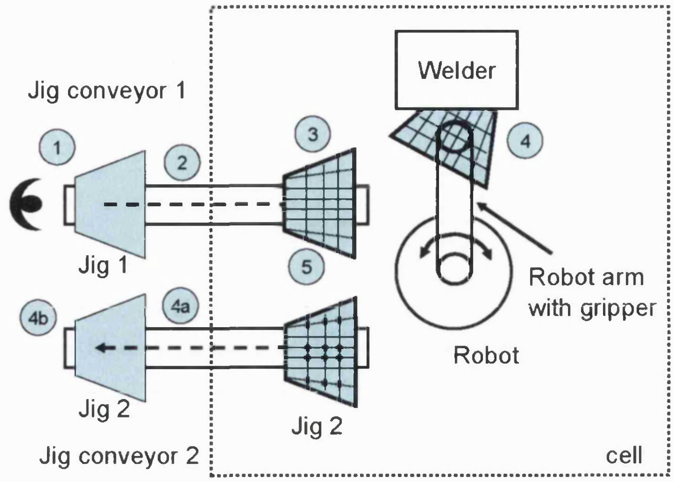
8 DFC Case studies 1 and 2

Two case studies which have been carried are presented here to show the application of the DFC methodology. The first case study is concerning a robot welding station at a local manufacturer of supermarket trolleys. The second study focuses on the design of a second version of the University of Bath changeover game.

8.1 DFC Case Study 1 - Shopping Trolley

The case study is presented to illustrate the 9-step methodology. It is based on a robot welding station in a local manufacturing business. The business in question offers a range of supermarket trolleys to accommodate their customers' preferences for different styles and sizes of trolleys. As a consequence frequent changeovers are experienced on their manufacturing equipment.

Part of the business is to manufacture meshes of steel wire for supermarket trolleys, which the station shown in Figure 8.1 is designed to do. During the operation of the station product specific jigs are manually loaded with the raw material. A NC robot manipulates these jigs so that the wires can be welded together using a stationary welding machine. There are two jigs per robot, so that one jig can be manually loaded by an operator, while the other is in use by the robot in the automated welding cycle. This is schematically shown in Figure 8.1.



Operating Procedure:
1. Operator unloads and loads jig 1
2. Jig is advanced into cell
3. Robot picks up loaded jig 1
4. Robot positions jig 1 between electrodes for different welds
   While operator will:
   a) convey Jig 2 with previously welded mesh to its loading/unloading position
   b) unload and reload jig 2
5. Robot places jig 1 with welded mesh back on conveyor 1

Figure 8.1 Layout of the robot welding cell

8.1.1 Phase 1 - Analysing and presenting the issues (Step 1-5)

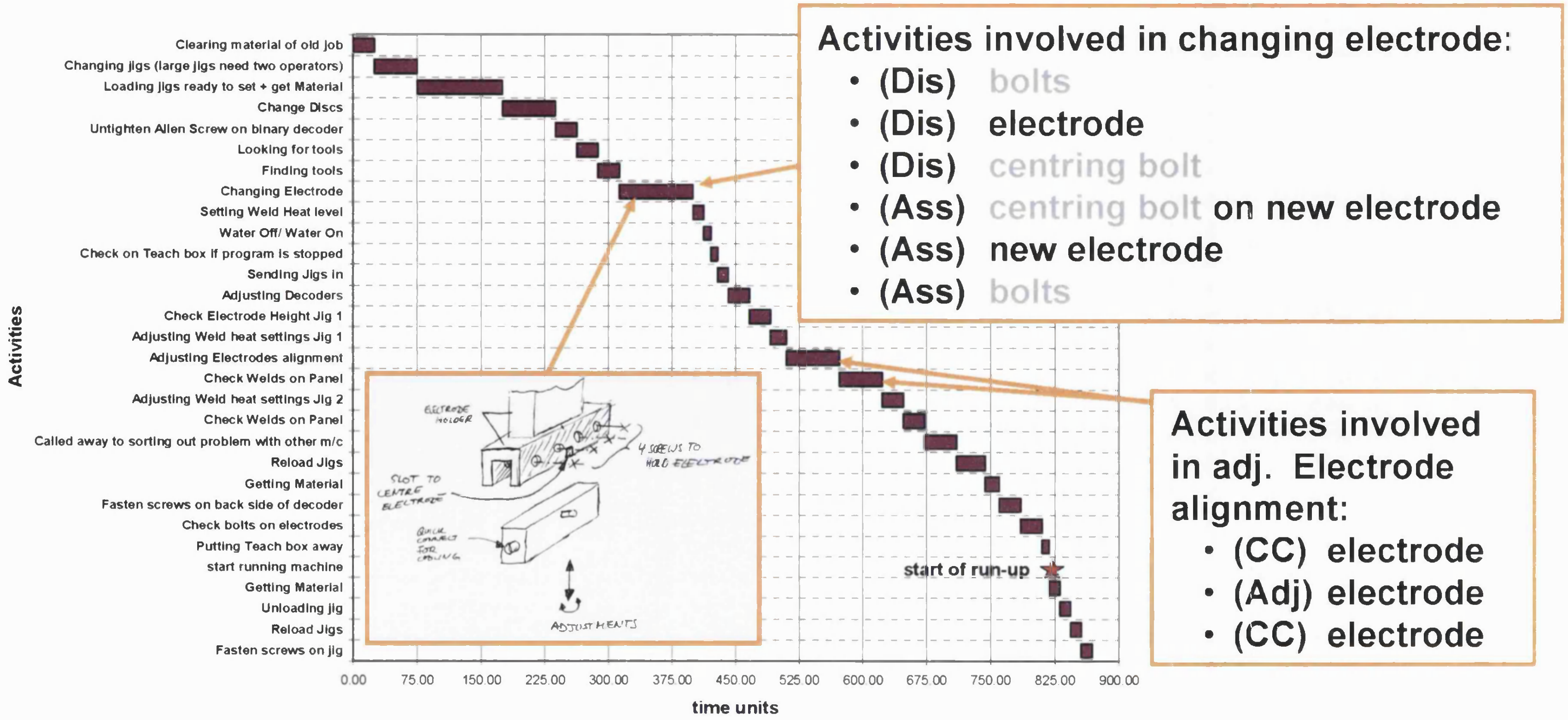
The drivers for changes which have been identified are the type and size of the wire mesh and the wire diameter.

Depending on the trolley types the following change elements had to be manipulated during a changeover:

- Jigs to hold wire mesh (one for each type)
- Binary Decoder
- Screws for the Binary Decoder
- Electrodes (one pair for each size of mesh)
- Centring bolt for the Electrodes
- Screws for the Electrodes
- NC program (one for each type of shopping trolley)

- Current Control (sets the "energy content" of the electrode which determines the weld heat)

The changeover activities related to these change elements have been identified as illustrated in the Figure 8.2. More details about the changeover activities associated with certain change elements can be found in the evaluation sheet in Figure 8.3. The key results of the design evaluation **before improvement** are shown in the Table 8.1.



colour code: **electrode** = Functional CE
centring bolt = Primary or Secondary Support CE

Figure 8.2 Identifying the changeover activities related to a change element (For confidentiality reasons the times shown in the figure are scaled)

original design													
change elements											Changeover Analysis		
change element	No. of elem.	Disassembly	Positioning or Setting	Assembly	Add. Time for purging/ cleaning	operation time/CE	adjustment?	add. t for adjustment	add. time for check.	total adjustm. time	total elem.s c/o time	nec. CE	nec. CE c/o time
	N	Dis [s]	Po [s] or Set [s]	Ass [s]	PC [s]	time/s	A_a	T_{aot}	T_{ac}	$T_{at}=T_{aot+Tac+Tp}$		E_n	
jigs (current)	2	23.00		0.00		23.00	0				46.00	2	46
jigs (new)	2			23.00		23.00	0				46.00	2	46
disc (current)	1	32.09		0.00		32.09	0			0	32.09	0	0
disc (new)	1			32.09		32.09	1			0	32.09	0	
binary dec.	2		12.50			12.50	0			0	25.00	0	0
screws	4	6.25		6.25		12.50	0			0	50.00	0	0
electrodes (current)	2	12.89	0.00	0.00		12.89					25.78	2	25.78
electrodes (new)	2		12.50	12.89		25.39	1	62.5	148.75	211.25	262.03	2	25.78
screws	8	5.00		5.00		10.00	0			0	80.00	0	0
centring bolts	2	1.50		1.50		3.00	0			0	6.00	0	0
Current on Electrodes	1		10.00			10.00	1	53.75	138.75	192.5	202.50	0	0
totals	27									sum:	807.49	8	143.56
												design efficiency	c/o activities
											Index	29.63%	17.78%

Figure 8.3 DFC Evaluation Sheet (Original Design)

Table 8.1 Key results of the DFC Evaluation before improvement

	Before
No of CE:	27
No of necessary CE:	8
Design Efficiency Index:	~30%
Total effort:	807.49 TU
Val.-added:	143.56 TU
CO Activities Index:	~18%

*TU=Time Units

Due to the process, the jigs, the computer disc with the NC program and the binary decoder with fasteners need to be replaced whenever a different product type is to be manufactured. Change in the overall product size requires the electrodes to be exchanged by electrodes of a different length. Replacing the electrodes and the changing of the weld heat level setting are dependent on the size of the product and the wires used.

The electrode is in contact with the product during the welding operation and thus is a functional change element (F-ECE). The electrodes' horizontal alignment is important for the process. This is achieved by a centring bolt inserted into a peg hole in the electrode, which centres the electrodes by fitting into a slot in the welding equipment. The centring bolt is a primary support ECE (PS-ECE) since it is vital for the right horizontal location of the electrodes. The electrodes are fastened to the welding equipment by 4 threaded bolts, which need to be removed and replaced in order to gain access to the old electrodes and to secure the new electrodes (see Figure 8.4). The fasteners therefore are secondary support ECEs.

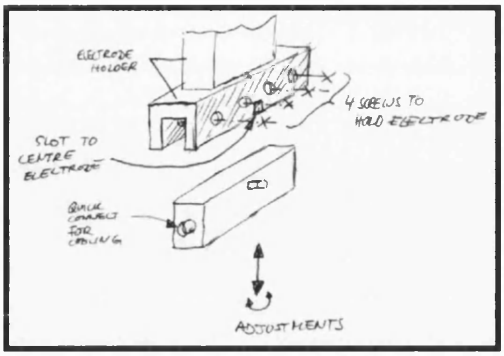


Figure 8.4 **Electrode bolted to welding station with 4 screws. Horizontal alignment achieved with a centring bolt.**

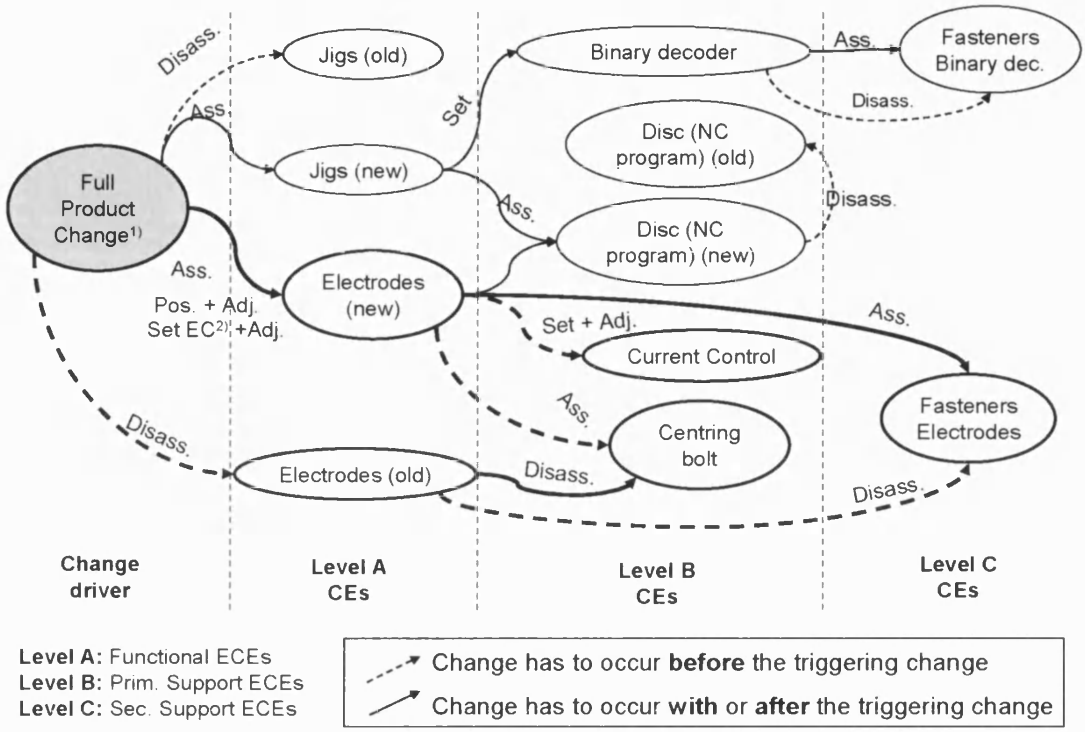
Using the change drivers identified earlier, changes can be decomposed into required changes to the change elements. Figure 8.5 shows what role the change elements play for specific change drivers.

A. **Functional ECEs**
B. Prim. Support ECEs
C. Sec. Support ECEs

Change Drivers		change elements															
Product Parameters	**Values**	**Jigs (type A)**	**Jigs (type B)**	**Jigs (type C)**	**Jigs (type D)**	Binary Decoder	Fastener holding Binary decode	**Electrodes (length 200mm)**	**Electrodes (length 250mm)**	**Electrodes (300mm)**	Centring Bolts for Electrodes	Fastener for Electrodes	Current on Electrode	NC Program (type A)	NC Program (type B)	NC program (type C)	NC program (type D)
Wire mesh type	type A	A				B	C	A			B	C	B	B			
	type B		A			B	C		A		B	C	B		B		
	type C			A		B	C		A		B	C	B			B	
	type D				A	B	C			A	B	C	B				B
Wire mesh size	small							A			B	C	B				
	medium								A		B	C	B				
	large									A	B	C	B				
Wires Diameter	0.5mm							A	A				B				
	0.7mm									A			B				

Figure 8.5 **Matrix mapping change drivers and change elements**

The change driver flow-down relationships for a full product change and its effect on the welding station electrodes are illustrated in Figure 8.6. At the top of the hierarchy is a certain change driver or a combination of change drivers. The other levels of the hierarchy are based on the three types of change elements.



1) Incl. change of mesh type and size and wire diameter
2) Setting Energy Content (EC) of electrodes to vary weld heat

Figure 8.6 The Change Driver Flow-Down Hierarchy

The change driver flow-down relationships are determined from the information presented in Figure 8.5 and the changeover activities related to the change elements.

The highlighted CEs and relationships of the change driver flow-down in Figure 8.6 are read in the following way:

> A change in the product triggers a disassembly change in the old/current electrodes (Level A), which in turn triggers disassembly tasks for the fasteners (Level C) and the centring bolt (Level B). The product size change also triggers an assembly task for the new electrode (Level A). The location and orientation of the new electrode is important and the position needs to be set. Also, depending on the number of simultaneous welds per electrode there might be a need to adjust the energy flow

from the electrode through the wires during the welding operations. This is described here as an "energy content" property of the new electrodes, which needs to be set and adjusted to satisfy weld quality requirements. This setting and adjustment is achieved by setting and adjustment of the current control (Level B), in this case by means of a turn-switch.

A major part of the changeover activity on this station was incurred by the desire to use electrodes which were as long as possible for the product specific jigs, with the objective to optimise the output volume. The duration of successive changeovers could be considerably reduced by standardising the electrode length for all products, but this would mean an increased average cycle time. In cases where batch sizes are very small and changeover frequency very high this trade-off could be beneficial for the overall efficiency of the equipment.

8.1.2 Phase 2 - Making Improvement (Steps 6-9)

Some improvement concepts generated by the procedure presented in Step 6 of the DFC methodology are listed in Table 8.2. Extensive work has been carried out by researchers and students at the University of Bath, who came up with improvement concept 1. In this concept the existing trolley design would be replaced by a modular trolley design such that no product type specific jigs would be needed for the manufacture of any trolley. Central to this are the use of universal datums and standards. Based on this a production concept with near-zero changeover time similar to automotive assembly lines was proposed (McIntosh, 2003).

Table 8.2 Sample improvement options with DFC evaluation and implementation costs

Concept	Change Element	Improvement Possibilities	Concept description	Comments	Reduction of CE count	Reduction of effort (in Time Units)	Implementation Cost
1	Jigs	Elimination of influence	New concept trolley	High initial investment	27	807.49	high
2	Jigs	Separation	Modules of jigs rather than product specific jigs	Product range not big enough to justify this	n/a	n/a	medium
3	Electrodes	Eliminate Influence	Keep same Electrode for all products	Due to wear electrodes have to be changed	0	0	Medium-high (lower output)
4	Electrodes	Eliminate Adjustment (Electrode alignment)	Standardised Electrode holder w/ quick release device		10	297.25	medium
5	Binary Decoder	Elimination of Influence	Influence of jigs can be eliminated by std. jigs		6	75	low
...	...	...	...	...	...		...

Concept 4 is another proposed improvement, which aims to reduce the effort currently required to disassemble and assemble the electrodes. Furthermore, it aims to reduce the adjustment currently required, both to the electrode's height and, to its alignment by providing standardised electrode holders. Such standardised holders allow alignment of the electrodes to be set offline. However, this task can be eliminated entirely if these standardised holders are used to skim electrodes during maintenance, thereby attaining a standard operating position and resulting in benefits of reduced set-up times. Other benefits are likely, which may include considerably shorter run-up and the production of less scrap.

The right-hand column of Table 8.2 shows the estimated implementation costs for the proposed concepts in a range from low to high. These results suggest that proposed concepts 4 and 5 have good cost/benefit ratios. These concepts have been selected for the purpose of the remaining sections of this paper.

The evaluation of the improved design is carried out as described in Step 9 using the DFC Evaluation Sheet. Key results of the evaluation **after improvement (Concepts 4+5)** are shown in Table 8.3. By implementing concepts 4 and 5 the design efficiency index could be raised from about 30% to about 73% and the CO activities index from about 18% to 35%.

Table 8.3 Key results of Evaluation of improved design

	before	after
No of CE:	27	11
No of necessary CE:	8	8
Design Efficiency Index:	**~30%**	**~73%**
Total effort*:	807.49 TU	396.96 TU
Val.-added*:	143.56 TU	143.56 TU
CO Activities Index:	**~18%**	**~35%**

*TU=Time Units

Further benefits which might be realised by these improvements include possibly improved maintenance procedures (Reik et al., 2005a).

8.2 DFC Case Study 2 - The University of Bath DFC Game

A changeover game had previously been developed by a student at the University of Bath with the purpose to illustrate typical changeover issues. The game consists of a machine with a mandrel, similar to a paper embossing machine. The machine was deliberately designed such that a range of issues will become apparent to the player. This section describes how the DFC methodology was applied to the original game to develop a second version with improved changeover performance. Although the second version still offers options for further improvements, in comparison to the original version, changeovers have still been improved very considerably. This section describes some results from various workshops involving one or both versions of the game.

8.2.1 The game play within changeover improvement workshops

Typically the game is played in groups, with each group tasked to perform a changeover in parallel on one embossing machine. The groups are each provided with their machine and the necessary change parts. Tools and other resources required have to be shared between the groups and are typically made available in a central 'store' to which all groups have access. A range of tools such as circlip pliers, a hammer and allen keys of various sizes are provided. Some of which are surplus to requirements, others are broken or otherwise difficult to use for the game.

Each group's task is to perform a changeover on their machine, achieving the best possible setting (quality of the changeover) in the best possible time. The aim of the changeover is to change the top roller with a roller of different diameter. To achieve the required quality the gap between the new top roller and the bottom roller must be set, such that the mandrel can 'process' a playing card.

The groups are given a brief introduction into what they are aiming to achieve. This introduction generally consists of little more than a brief explanation of what the machine is meant to do, what needs to be exchanged and how it needs to be set-up. Also, the teams are introduced to the performance measures used to assess each team's performance.

Figure 8.7 Industrialist playing the University of Bath changeover game

The performance of the groups is measured by recording the changeover times which are achieved and by assessing the quality of the changeover, where good changeover quality is achieved when the gap between the two rollers is set such that it is tight enough so the machine can pull a playing card through without slip, but also wide enough so the machine does not get stuck if the operator holds on to the playing card. In addition, it is checked whether appropriate bolts, screws and shims are used and bolts tightened.

Once the groups have finished the changeover, they are asked to identify improvement options. This is typically done in two stages: first, identification of retrospective improvement options and, second, identification of improvement options which would be available if re-design of the machine was considered. In both cases they are asked for their estimated target changeover time. Results of this will be presented as part of the re-design of the changeover game in the following sections.

8.2.2 The original University of Bath Changeover Game

As has been mentioned before the original machine used in the game was deliberately designed such that changeovers are complicated and adjustments tedious. This was done with the particular aim to demonstrate to participants the considerable impact of process equipment design on changeover performance.

Figure 8.8 shows a section of the changeover game illustrating some of its main parts. The aim of the process is to emboss paper by means of a top roller with the imaginary embossing logo pressing paper against a free rolling bottom roller. A motor (crank lever) drives the top roller via a set of gears. When setting the machine (i.e. the gap between top and bottom roller), the gear meshing also needs to be adjusted accordingly. This is done by raising or lowering the motor block (see Figure 8.9). The measure of changeover quality when assessing participants' performance also takes gear meshing into account. A too tight or too lose mesh will decrease the quality rating. More details regarding the changeover process of the original machine are provided in the next section.

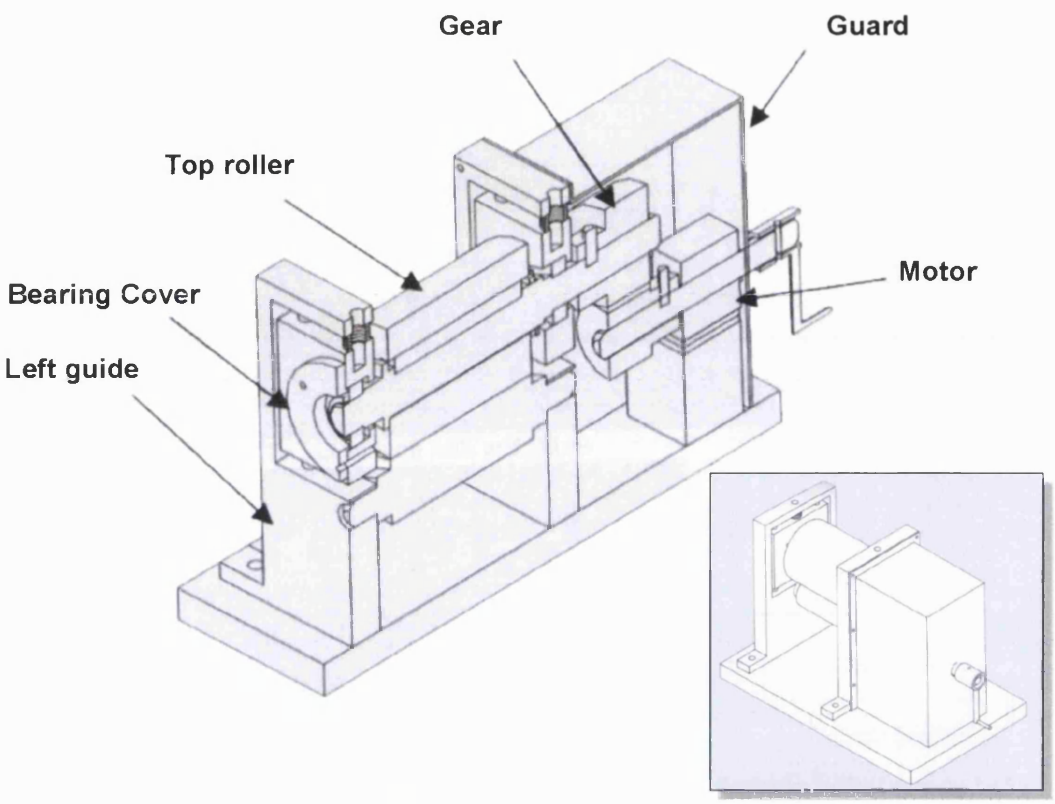


Figure 8.8 **CAD drawing of the embossing machine and part description (Drawings from Escott)**

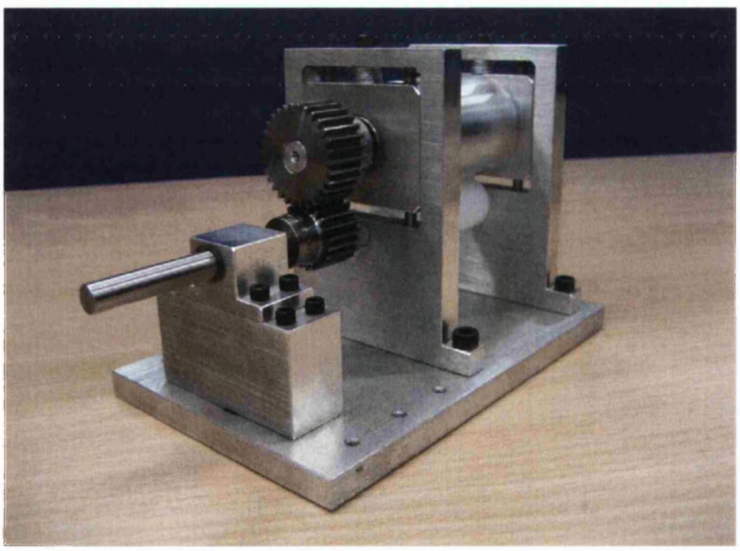


Figure 8.9 **The original University of Bath changeover game – simulating changeovers of a paper embossing mandrel**

8.2.3 Application of the DFC methodology

As part of the author's work a new version of the game has been designed using the DFC methodology presented in the previous chapter. This is described in the following sections.

Phase 1 - Analysing and presenting the issues (Step 1-5)

Product variation in the imaginary process can for example comprise different embossed logos and different paper sizes. Table 8.4 shows two imaginary products. When it is assumed that the process should emboss one logo per page, both variety parameters are dependent on the design and dimensions of the top roller (engraved logo, and top roller width and circumference, respectively). Thus, one change driver, namely the product type, is sufficient to represent the driving forces behind the changeover activities.

Table 8.4 Current Product Range

	Change Driver: **Product Type**	
Product Name	*Variety Parameter A:* **Embossing Logo**	*Variety Parameter B:* **Paper size**
Embossed Paper A	Logo of Company A	large
Embossed Paper B	Logo of Company B	small

The top roller needs to be exchanged when a new product is to be manufactured. The current and the replacement top rollers are both in contact with the product and are thus functional CEs. When the diameter of the current and the replacement top roller are different the gap between the top roller and the bottom roller needs to be reset. The machine is designed such that setting of the gap is achieved by tightening the top roller bearing slides with height adjustment screws against height adjustment shims (see Figure 8.10). The right amount and type of these height adjustment shims is vital to provide the required gap setting. The height adjustment shims are classified as primary support CEs (PS-ECEs) and the height adjustment screws as secondary support CEs (SS-ECEs).

The setting of the gap between top and bottom roller in turn requires the setting of the distances between top roller and motor shaft such that the gears mesh properly. This is also achieved by introducing various shims under the motor bearing housing. As the motor bearing height and the correct motor bearing shims are vital for the proper functioning of the process, both of these CEs are classified as PS-ECEs.

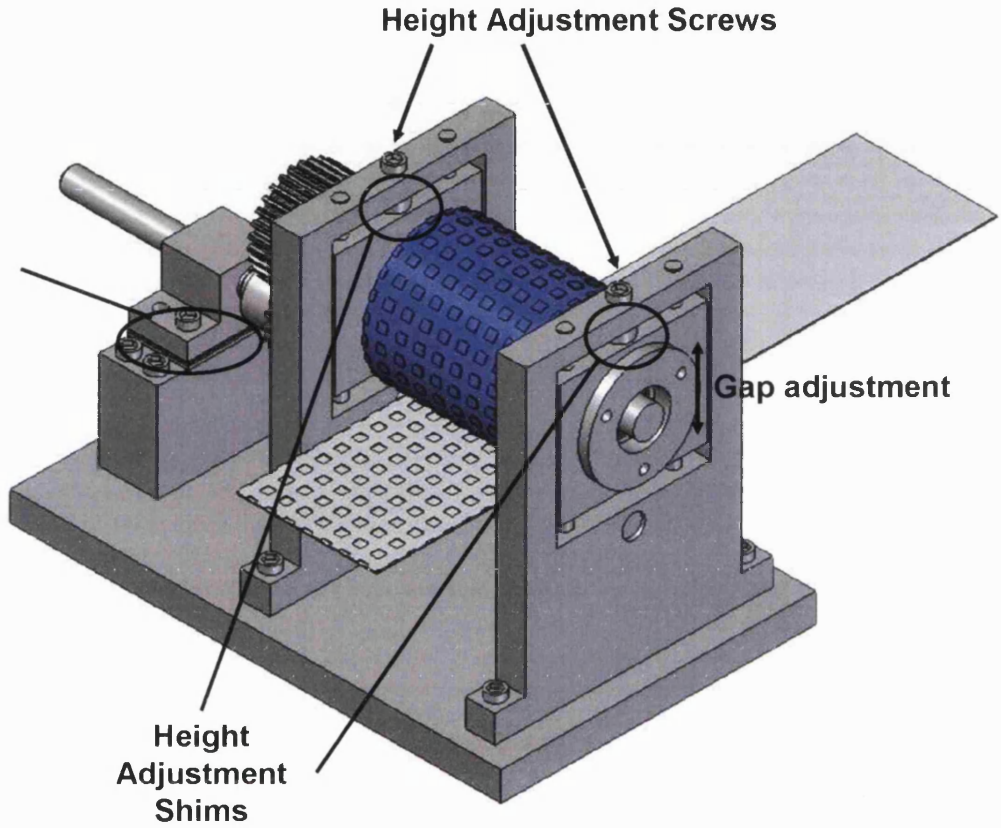


Figure 8.10 Setting of roller gap and gear meshing with shims on original version of the game (Drawings from T. Howard)

The change elements which have to be manipulated during a changeover are listed in Table 8.5. In total there are 29 different Change Elements, of which only 2 are functional CEs (F-ECEs). This results in a Design Efficiency Index of 7%.

Figure 8.11 shows recorded changeover time of a changeover performed by the author. The times of the changeover activities were measured for individual change element manipulations, such as assembly, disassembly and adjustment. In total 19m 53s were needed to perform a complete changeover. The duration of value-added activities, which by definition are only those activities which manipulate Functional-CE, is only about 19 seconds. This equates to a Changeover Activities Index of about 2%. The key results **before improvement** are summarised in Table 8.6.

Table 8.5 List of Change Elements of original changeover game

Change Elements (CEs)	no of CEs	necessary CEs
top roller (current)	1	1
top roller (replacement)	1	1
Safety Cover Screws	4	0
Safety Cover	1	0
Roller Centering Washers (Left)	2	0
Left Guide Assembly	1	0
Left Guide Screws	2	0
Roller Bearing Cover (Left)	1	0
Roller Bearing (Left) Circlip	1	0
Roller Bearing Cover (left) Screws	3	0
Height Adjustment Screws	2	0
Height Adjustment Shims (old) [1)]	2	0
Height Adjustment Shims (new) [1)]	2	0
Motor bearing shims	1	0
Motor bearing	1	0
Motor Bearing Screws	4	0
total	**29**	**2**

[1)] For simplification shims have been grouped into 'packs of shims' with the required height to achieve the gap setting

Table 8.6 Key results of DFC Evaluation before improvement

	Before
No of CE:	29
No of necessary CE:	2
Design Efficiency Index:	**~7%**
Total effort:	19m 53s
Val.-added:	19s
CO Activities Index:	**~2%**

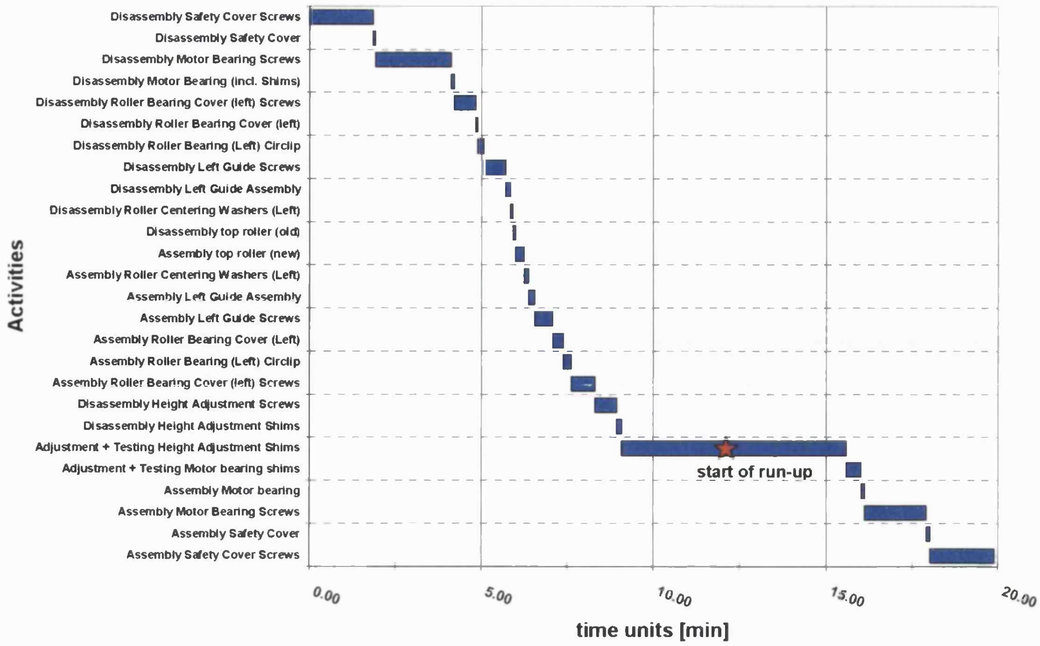


Figure 8.11 Sample changeover procedure for the changeover game, with recorded times for individual activities

Using the change driver identified earlier, changes can be decomposed into required changes to the change elements. Figure 8.12 shows what role the change elements play for specific change drivers.

The change driver flow-down relationships and the required settings for the case of a product type change are illustrated in Figure 8.13. At the top of the hierarchy is the change driver. The other levels of the hierarchy are based on the three types of change elements.

A - Functional ECEs
B - Primary Support CEs
C - Secondary Support-CEs

change driver		top roller (new)	top roller (old)	Roller centring washers (left)	Left Guide Assembly	Left guide srews	bearing cover (left)	bearing cover (left) screws	circlip (left) top roller	Height Adjustment Screws	Height Adjustment Shims (old)	Height Adjustment Shims (new)	Motor bearing	Motor bearing Screws	Shims for Motor bearing	Safety Cover	Safety Cover Screws
Product Type	Embossing Logo	A	A	B	C	C	C	C	C	B	B	B	B	C	B	C	C
	Paper Size	A	A	B	C	C	C	C	C	B	B	B	B	C	B	C	C

Figure 8.12 Matrix mapping change drivers and change elements for the changeover game

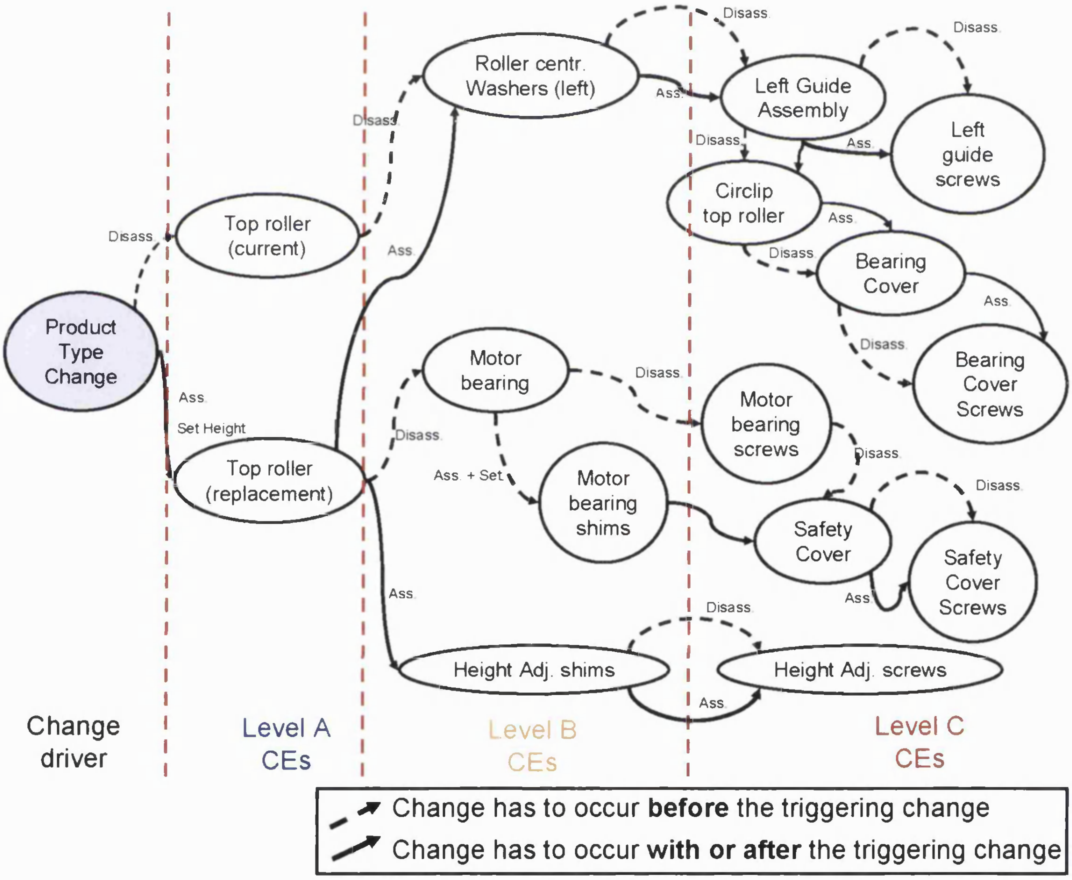


Figure 8.13 The Change Driver Flow-Down for the University of Bath Changeover Game

Phase 2 - Making Improvement (Steps 6-9)

Three main causes for long changeovers can be identified using the DFC Analysis and the Change Driver Flow-Down (see Figure 8.13). These are:

- Assembly and disassembly of many parts required to gain access to the top roller
- Height adjustment of the top roller, including trial and error iterations, is very cumbersome and time consuming
- Setting the height of the top roller requires setting the height of the motor bearing block, which is also a time consuming task

Some improvement options generated by the procedure presented in Step 6 of the DFC methodology are listed in Table 8.7.

Table 8.7 Sample improvement options with DFC evaluation and implementation costs

	Change Element	Improvement Possibilities	Concept description	Comments	Reduction - CE count	Reduction. - effort	Cost
1	Top Roller/ Motor bearing	Elimination of Influence	Keep top roller at same height position	Bottom roller becomes extra change elem.	11	~500s	high
2	Top Roller	Separation	Split top roller into two halves	Possible Quality issues?	23	~1100s	high
3	Top Roller	Reduction of Adjustment Effort	Use eccentric bearing housing to adjust top roller height	More CEs but easier adjustment	-2	~300	medium
4	Top Roller	Grouping	Pre-set top roller assembly	Bigger change element	10	~600s	Medium-high
5	Motor bearing	Elimination of influence	Chain drive with tensioner		11	~500s	medium
6	Motor bearing	Elimination of influence	Drive bottom roller	Possible Quality issues	11	~500s	medium
8	Bearing Cover	Reduce Securing Effort	Use same screws, shorter screws		0	~15s	low
..	...	...	...	...	...		...

Figure 8.14 illustrates some of the improvement options. Improvement option 1 (see Figure 8.14a) attempts to eliminate the influence of a top roller change on the motor bearing by adjusting the height of the bottom roller rather than the height of the top roller. Improvement option 4 (see Figure 8.14b) seeks to improve the access to the top roller by grouping the top roller into a pre-set module with the bearing and part of the guides. This can reduce the required effort to change top rollers dramatically; however, has the disadvantage of increasing change element size and their cost. Similar to Improvement Option 1, Improvement option 5 (see Figure 8.14c) seeks to eliminate the influence of the top roller height change on the motor bearing by replacing the set of gears with a belt drive with tensioner.

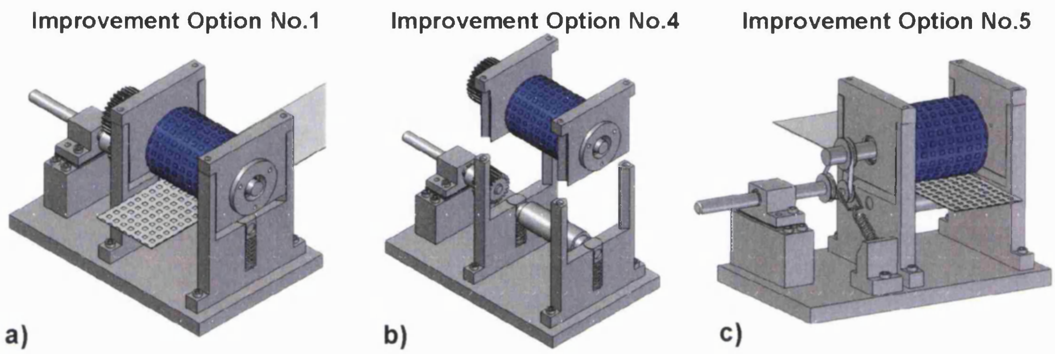


Figure 8.14 Concept drawings of selected improvement concepts (Drawings done by T. Howard)

The right-hand column of Table 8.7 shows the estimated implementation costs for the proposed options in a range from low to high. Improvement options 3 and 4 were selected to be taken forward and were developed into an improved changeover game version, as their embodiment promised a more robust game which would better resist wear in a 'hostile' workshop environment. The improved concept is shown in Figure 8.15. It consists of two top roller assemblies, which can be preset using an eccentric bearing housing. The top roller is driven with a tooth belt. Tensioning of the tooth belt is achieved by sliding the motor block on the base plate. This allows a fast and easy exchange of the top roller assembly.

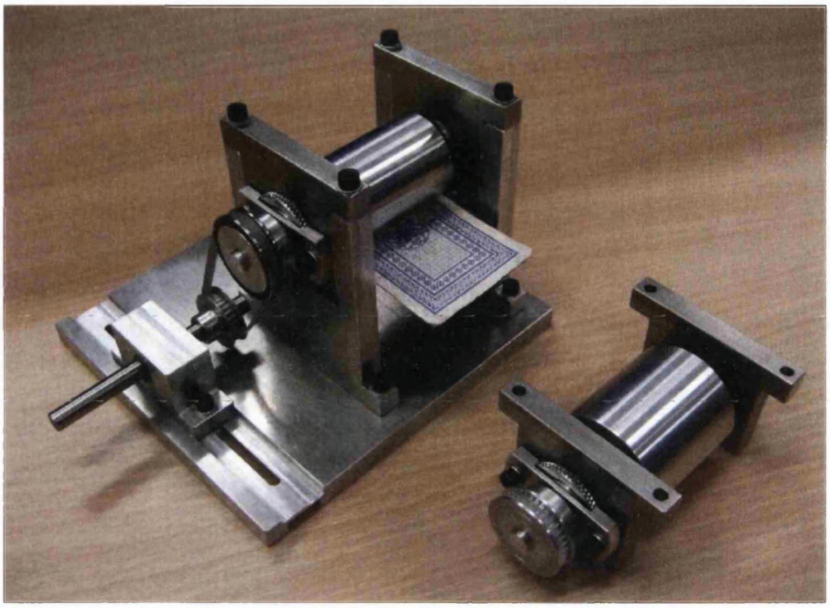


Figure 8.15 The improved version of the University of Bath Changeover Game

The evaluation of the improved design is carried out as described in Step 9 using the DFC Evaluation Sheet. Key results of the evaluation **after improvement (Options 4+5)** are shown in Table 8.3. By implementing options 4 and 5 the design efficiency index could be raised from about 7% to about 14% and the CO activities index from about 2% to about 5%.

Table 8.8 Key results of Evaluation of improved design

	before	after
No of CE:	29	14
No of necessary CE:	2	2
Design Efficiency Index:	**~7%**	**~14%**
Total effort*:	19m 53s	6m 24s
Val.-added*:	19s	19s
CO Activities Index:	**~2%**	**~5%**

The improved version was built to show workshop participants the possible improvement which can be achieved by focused re-design. The next section reports of the results recorded during various workshops with students and industrialists carried out by the author and his colleague Dr Richard McIntosh.

8.3 Discussion

Two case studies have been presented in this chapter. Both have been selected to show the application of the full nine steps of the DFC methodology developed in Chapter 7. They show the usefulness of the proposed methodology to analyse and subsequently improve the changeover performance of manufacturing equipment.

The requirements for a DFC methodology were discussed in Chapter 6 in respect of three core aspects, namely modelling of changeover processes, evaluation of changeoverability and design guidance. Regarding these aspects, the following conclusions can be drawn from the application of the DFC methodology in this chapter:

- **Modelling Changeovers:** It has been shown how the basic concepts of the DFC methodology, such as Change Drivers, Change Elements and Changeover Activities can be used to model changeovers. The concepts provide the fundamental building blocks for describing changeovers and analysing them. Part of this is the Change Driver Flow-Down which provides a hierarchical overview of what happens during a changeover.

- **Evaluation:** Several measures have been proposed to evaluate changeover performance. Beside the Design Efficiency and Changeover Activity Index, the number of Change Elements has been proposed as a changeover performance measure. The case studies have shown that the indices are only good as a comparative measure when little design change has occurred between the original and the improved design. When more fundamental design changes have happened the indices are likely to not reflect accurately the degree of improvement. However, the number of Change Elements as a measure for 'changeoverability' has proved to be a good measure in the case studies. This will be further discussed in the next chapters.

- **Design Guidance:** Through the hierarchical approach based on the Change Driver Flow-Down the DFC methodology allows systematic isolation and reduction of the interdependencies between product variety and CEs, and between different individual CEs. Equally the reduction of effort and time required for a changeover is supported by systematically addressing individual Changeover Activities. This has worked well in some of the improvement options identified in the case studies presented here. However, it failed to provide sufficient guidance when more fundamental design improvement options are being sought.

The latter point suggests that in some cases a wider search space is needed in order to find significant improvement. The structured search for design improvements within the 9 step methodology is based on the Change Driver Flow-Down. Although, this graphical and hierarchical representation can be helpful in displaying and identifying improvements, it is essentially bound to the embodiment of the analysed design as specific CEs are considered. A more fundamental re-design is required if changeover improvement targets can not be achieved by improvements identified through this methodology. This has been done in the case of case study 3 and is reported in Chapter 10. For this purpose the DFC methodology has been slightly revised and its deployment within conceptual design is described in the following chapter. Thus, the integration of DFC and conceptual design allows the design search space to be opened up and potentially new concepts to be identified.

9 Revision of the DFC methodology

Previous chapters have developed a Design for Changeover methodology and have applied it in different case studies. The previous chapter also discussed some of the lessons learnt from these case studies. Although it has been shown that the 9-step methodology can be very helpful in identifying and evaluating improvements, in some circumstances it fails to provide sufficient guidance to identify good improvements. This, it is proposed, is the case as the improvement concepts in the 9-step methodology are mainly based on the identification and classification of CEs.

Focussing on the number of CEs in a design has been identified and validated as a good measure for the changeover performance and, thus, to compare different design options. However, as basis for improvements CEs are close to the physical design of the current machine and provide little room for more fundamental design alterations. If a more revolutionary improvement is being sought, re-design again has to start in the conceptual design phase.

This section will review the process of conceptual design and proposes that this shortcoming can be overcome by integrating DFC into the conceptual design process (Pahl and Beitz, 1996, Ulrich and Eppinger, 2000).

9.1 Conceptual Design

Pahl and Beitz (Pahl and Beitz, 1996) describe conceptual design as the process in which the requirements or design specifications are transformed into the specification of "principle solutions". The process can be described by a series of steps, which need to be undertaken in order to select the most promising principle solution. The steps are shown in Figure 9.1. The conceptual design process begins with the abstraction of the essential problems and the establishing of overall functions as well as sub-functions. The aim of these steps is to formulate problems in a general way, in order to avoid any possible limitation of the designer by fixed or conventional ideas.

Pahl and Beitz recommend as part of this a systematic broadening of the problem formulation for example by extending, or even changing, the original problem before thinking immediately of possible improvements to the existing situation. This way, better solutions for the overall problem might be found (Pahl and Beitz, 1996).

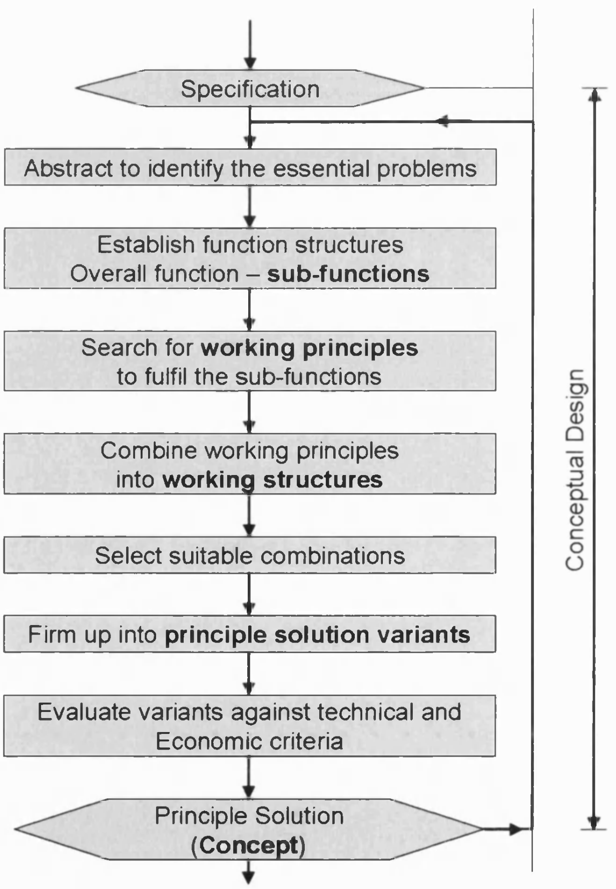


Figure 9.1 **Steps of the conceptual design process after Pahl and Beitz (Pahl and Beitz, 1996)**

Once the problem has been accurately formulated, the overall function needs to be described as the relationship of inputs and outputs of a plant, machine or assembly. These relationships between inputs and outputs can be expressed as energy, material and signal flows in a block diagram (Ulrich and Eppinger, 2000, Pahl and Beitz, 1996). Equally the overall function can be broken down into **sub-functions** and the energy, material and signal flows between these shown. Decomposition of functions is useful to facilitate solution finding for complex problems (Ulrich and Eppinger, 2000, Pahl and Beitz, 1996). The sub-functions can then be combined into a simple and unambiguous **function structure** (Pahl and Beitz, 1996), which allows designers to distinguish between those sub-systems for which solutions already exist and those for which new solutions need to be developed. The depth to which functions are being broken down "is determined by the novelty of the problem and also by the method used to search for a solution" (Pahl and Beitz, 1996).

The function structure then provides the basis for the search of suitable **working principles** for the individual sub-functions. Ulrich and Eppinger (2000) differentiate between internal and external search for solutions of sub-problems: using lead users, experts, patents, literature and benchmarking as part of an external search to identify existing solution concepts; or using the personal knowledge and the creativity of individuals or groups to identify new solution concepts. In this search process a systematic approach using classification schemes is often useful as it can stimulate the search in different directions. For example Pahl and Beitz suggest the classification of concepts for a machine with the function "form support wire" by the principle motions of two tools (punch and die). Figure 9.2 shows such a classification of possible basic motions for the assembly stage of the manufacturing hardware considered in Case Study 3. An example for classifying different working principles for the various sub-functions of the same machine is shown in Figure 9.3.

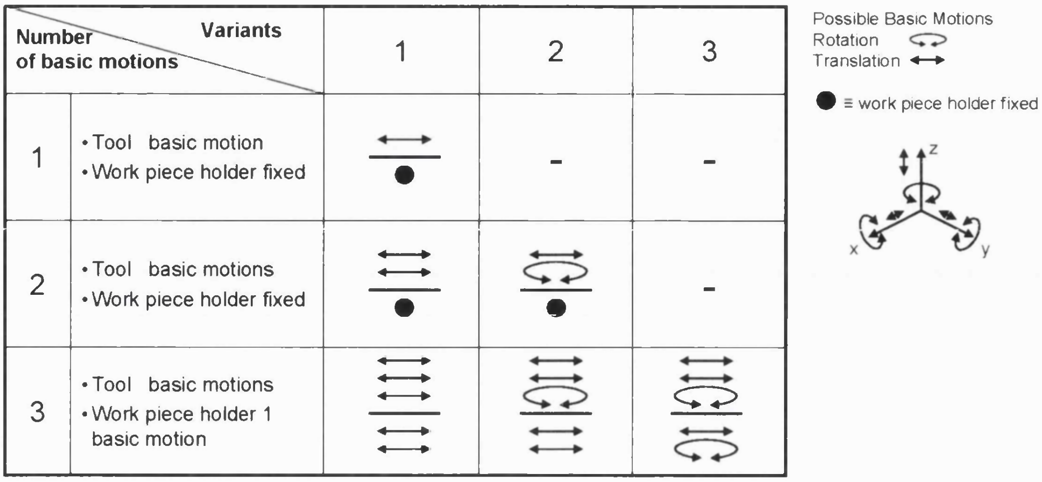


Figure 9.2 **Possible basic motions of tool and work piece holder in the assembly stage of the FAC machine in Case Study 3 (Based on work by Pahl and Beitz (1996))**

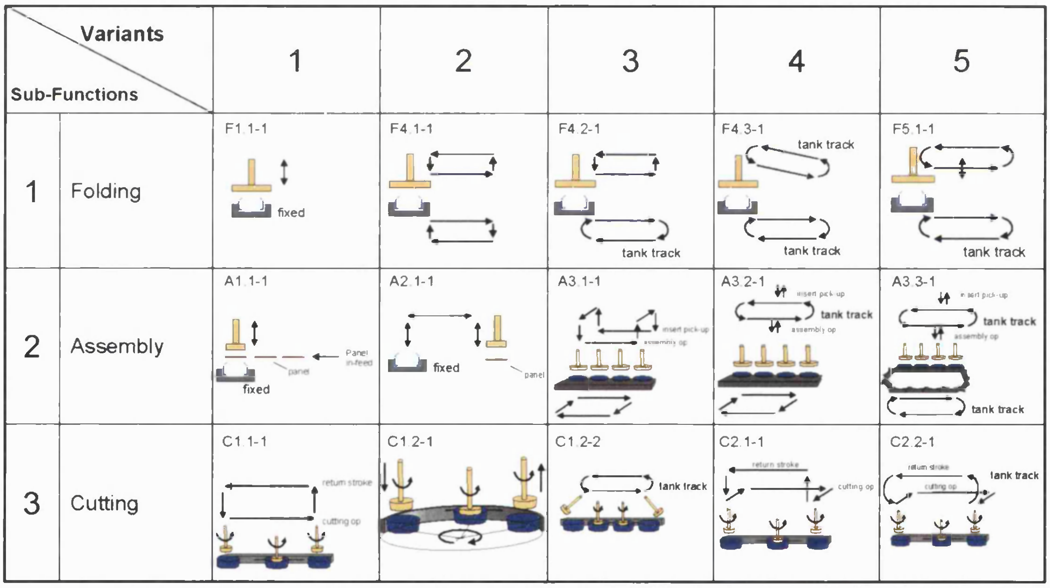


Figure 9.3 **Classification scheme for the FAC machine from DFC Case Study 3(Based on work by Pahl and Beitz (1996))**

Also, the presentation of concepts using classification schemes can help in the selection of good combinations of working principles (Pahl and Beitz, 1996). The working principles can be combined on the basis of the function structure, and the result is a

working structure. Usually a number of different working principles can be found for a particular sub-function (as shown in Figure 9.3) and, hence, a number of possible working structures can be created (Pahl and Beitz, 1996). When combining the working principles it is important as well to ensure physical and geometrical compatibility, but also the technical and economical feasibility of the combinations need to be considered (Pahl and Beitz, 1996). This can be greatly assisted by the use of a morphological chart as shown in Figure 9.3.

Once possible combinations have been identified, suitable working structures need to be selected such that these can be further detailed into **principal solution variants**. Through the systematic approach of selecting working principles on the basis of the sub-functions it is ensured that technical functions of the product are being fulfilled. However, there are also a number of other general or task-specific constraints which a solution needs to satisfy, such as safety, ergonomics, production, quality control, assembly, transport operation, maintenance, recycling and expenditure (Pahl and Beitz, 1996). Usually further detailed analysis of the working principles will be needed to check whether a particular solution satisfies the specific requirements. This can often, for example include more detailed drawings, sketches or rough calculations (Pahl and Beitz, 1996).

Although shown as a linear process, in reality this is not the case and there are likely several loops of parts or of all of the outlined steps necessary to find a working concept which satisfies all the requirements.

9.2 Integrating DFC and Conceptual Design

The previous section has given an overview of the conceptual design process. It has already been identified that the DFC methodology in its current state of development lacks guidance for substantial equipment re-design. In particular this is the case, as it is bound by the physical design and embodiment of the current machine because its search for improvements is based on the hierarchical relationships between CEs. In other words the current DFC methodology concentrates on finding improvement options within an already defined and selected working structure. This limitation in the design search space can be overcome by integrating DFC with the conceptual design process described above. The widening of the search space by abstraction of the problem formulation and by the use of systematic approaches is illustrated in Figure 9.4.

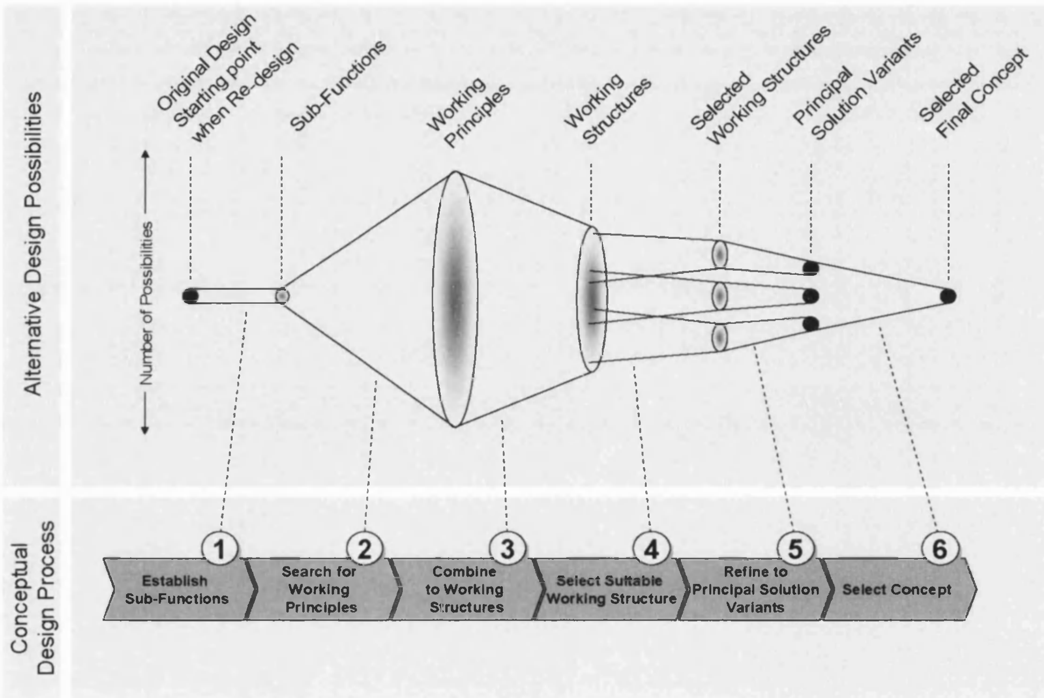


Figure 9.4 Alternative design possibilities during the conceptual design process

Considering the discussion above the DFC process can then be revised such that a widened search space is available when needed. This revised process which integrates conceptual design and the DFC methodology is illustrated in Figure 9.5.

The figure shows that there are two starting points for this revised DFC methodology. One starting point for the redesign of existing equipment designs (Starting Point 1 in Figure 9.5) and one starting point for the design of new manufacturing equipment (Starting Point 2 in Figure 9.5).

Following this new process when seeking improvements for an already existing original design (Starting Point 1), the first seven steps of the DFC methodology are applied before a decision whether the improvements identified are sufficient and can be achieved in an economically feasible way is made. If this is the case the methodology follows through with the last two steps of the original DFC methodology. However, if no solutions with sufficient improvement can be found the methodology guides the designer through the conceptual design process from establishing sub-functions to the refinement of working structure into principal solution variants.

In the case of a new and original design this point is used as a starting point (Starting Point 2 as shown in Figure 9.5). The process then starts immediately with the conceptual design process and the establishment of principal solution variants.

Once the conceptual design process is terminated the principal solution variants are then evaluated using the analysis part of the original DFC methodology. The best solution variant can then be selected based on the results of the DFC Analysis and other criteria and constraints as described as part of the conceptual design process in the previous section (Pahl and Beitz, 1996, Ulrich and Eppinger, 2000).

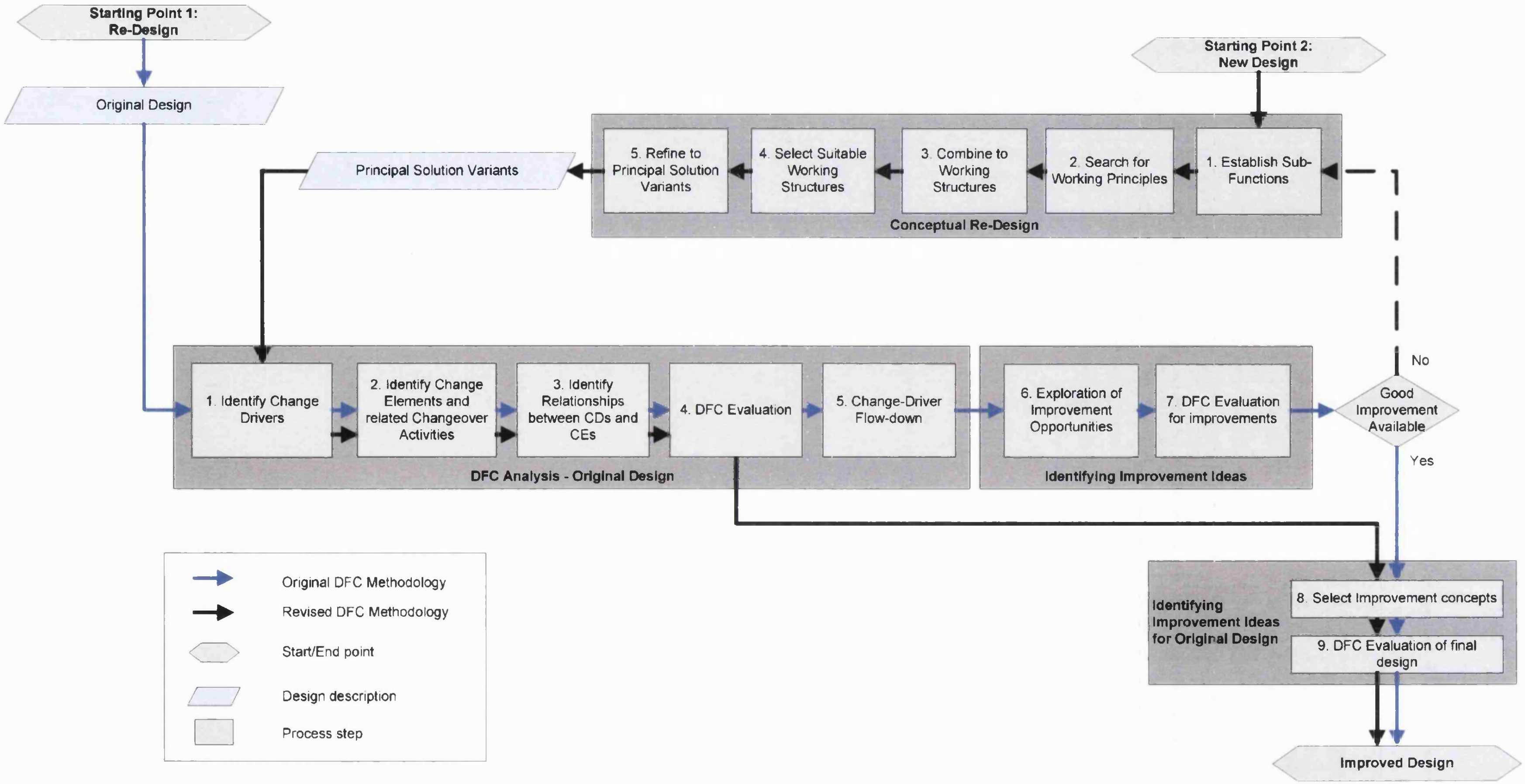


Figure 9.5 The Integrated Design for Changeover Methodology

9.3 Conclusions

Previous sections have identified that the design search space of the original DFC methodology can be limited as it is relying on CEs as the basis of improvement identification. This section has proposed how a general conceptual design approach can be integrated into the DFC methodology.

Two entry points to the methodology are provided depending on whether existing equipment is re-designed (Starting Point 1) or whether a more fundamental re-design is undertaken (Starting Point 2). In a retrospective improvement environment Starting Point 1 improvement cost and time to implement are crucial criteria. Therefore Starting Point 1 is more likely to satisfy these criteria. However, in the case that this does not yield sufficient improvement, the user is guided to Starting Point 2. If new equipment is purchase or designed, the DFC methodology should always be started with Starting Point 2.

The revised DFC process makes extensive use of the evaluation techniques which have been developed within the DFC methodology and have been successfully validated in the case studies in the previous chapter. Using further techniques to widen the design search space within conceptual design, the integration of DFC and conceptual design allows the shortcomings of the DFC methodology which have previously been identified to be overcome.

The following chapter describes a case study in which the revised DFC approach has been successfully implemented.

10 DFC Case study 3

The previous chapter has shown how DFC can be conceptually adopted to evaluate changeover performance during early stages of the design of manufacturing equipment. A case study has been carried out with an international manufacturer of packaging products who was in the process of re-designing a machine which manufactures a range of two-piece closures. The case study was set-up to investigate possible alternative design concepts for the machine. The revised DFC methodology from the previous chapter was utilised for this. The results of this study and the usefulness of the DFC evaluation techniques in the conceptual design process are discussed in this chapter.

10.1 The two-piece IDEAL closure range and its manufacturing process

As noted above, the machine under consideration manufactures two-piece closures as shown in Figure 10.1. The first part of the closure is the metal panel with a sealing compound which provides the means to form a seal on the container. The second part, the threaded plastic band, provides a means to secure the closure assembly on the container. The detachable anti-tamper portion of the band provides evidence that the closure seal has been broken. The anti-tamper band is an integral part of the plastic band which has been manufactured by injection moulding. A post-cutting process leaves only a series of small bridges connecting the anti-tamper band with the main band (see Figure 10.2).

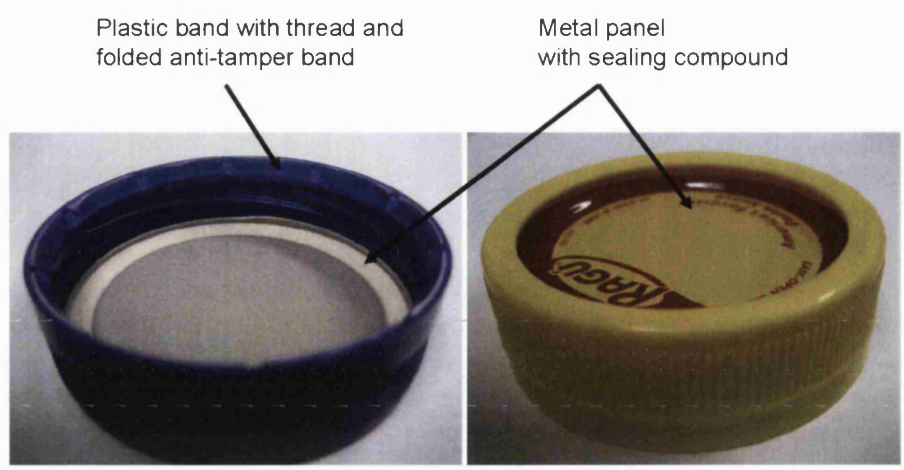


Figure 10.1 The two components of the IDEAL closure

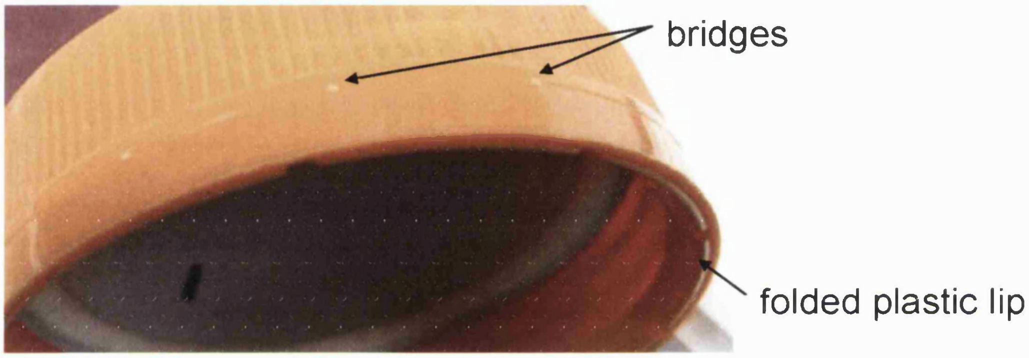


Figure 10.2 Detailed view on anti-tamper band with bridges

In total 59 process steps are required to manufacture the closure which includes manufacturing of components, conveying, sorting and packaging. Although the two-piece design of the closure is more expensive and extra process steps are required, it offers added value to the customer as it reduces the closure opening torque significantly. This is of particular interest for senior customers who often experience difficulties opening traditional one piece metal or plastic closures.

The case study presented here is concerned with the re-design of the so called FAC (Folding, Assembly and Cutting) machine (see Figure 10.3). The main function of the FAC machine is to assemble the two-piece closures. Besides this, the machine performs folding and cutting processes necessary to provide the closure with its tamper-evident functionality.

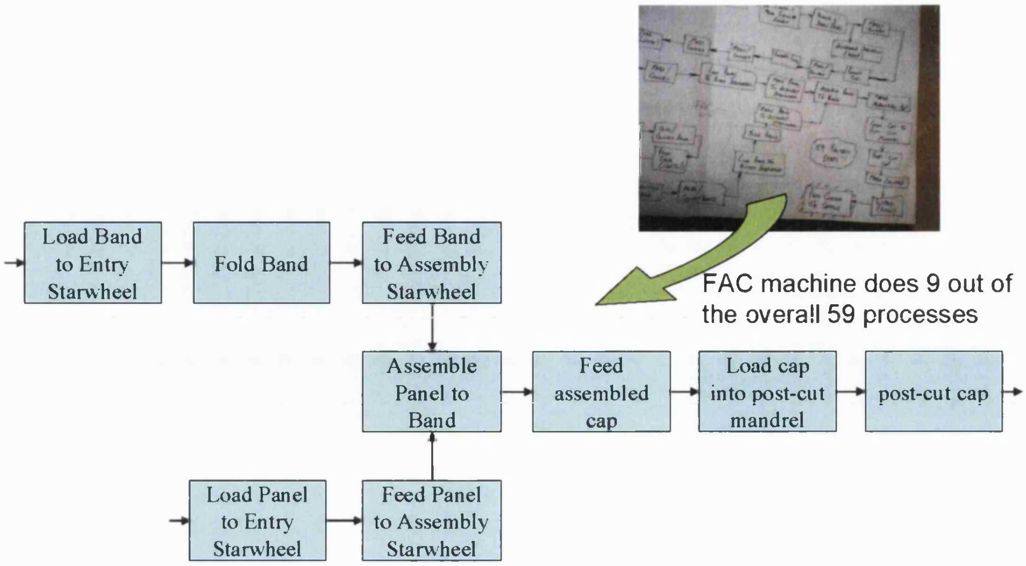


Figure 10.3 The 9 process steps carried out by the FAC machine

Originally, the closure range was manufactured by three dedicated lines, one each for three different closure sizes. Changeover on the original, dedicated FAC is extremely difficult primarily because of the design of the drive train. A complete strip-down would be necessary to change all necessary parts of the machine. This includes for example draining of the gear box which connects the drive to the individual turrets. Also, by making the design of the original FAC machines specific to closures size, the changeover to some sizes becomes impossible simply due to space constraints.

As new equipment had to be purchased for the European market, a re-design of the original machine was undertaken with the aim of using one machine to produce the whole current closure range. The machine also had to be capable of producing possible further sizes which might be added to the range in the future. A good changeover performance was therefore a main aim of the re-design and a target changeover time of 2-3 hours was set.

10.2 Initial re-design of the FAC machine

It was recognised by the company's engineering department that the rotary design of the original machine inhibits very fast changeovers, however, commitments to supply initial customers required pragmatic decisions in terms of what will be changed in order to fulfil the tight time constraints. It was decided that initially the machine was re-designed without altering the way the machine was processing the closures, as this would significantly reduce the amount of testing and prototyping necessary. Beyond that, a second phase re-design was also planned to have available a more flexible manufacturing line, once the product range has been successfully launched, justifying further investment. The two phases of the re-design together with the applied tools and techniques are illustrated in Figure 10.4.

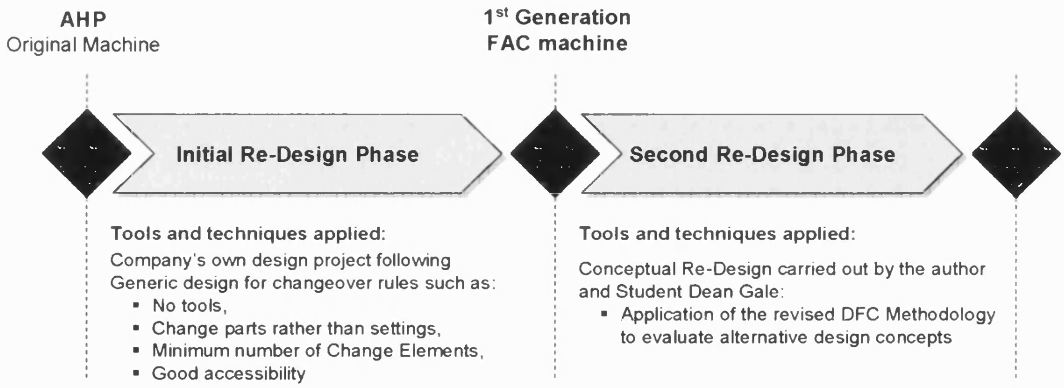


Figure 10.4 Phases and stages in the re-design of the FAC machine

The first re-design has been done by CROWN engineers. During the re-design the CROWN engineers aimed to minimise the number of change elements and to satisfy good design for changeover principles, such as no tools, change parts rather than settings and good accessibility. Also, best practice design principles witnessed on other manufacturing hardware have been considered. One example is the Rapid Changeover Parts (RACOP) design used by Zepf Technologies UK (ZEPF, 2006).

During the second phase of the re-design, as shown in Figure 10.4, the revised Design for Changeover methodology was applied by the author and project student Dean Gale. Using the DFC evaluation techniques the 1st generation FAC machine was analysed and an investigation into possible design alternatives was carried out. The results of this case study are presented in this chapter.

10.3 Application of the DFC methodology

This section describes the application of the revised DFC methodology. The Steps 1-5 of the original methodology are initially followed. The aim of this case study is to investigate alternative process design options. Thus, it was decided to pursue a major conceptual re-design, which is described in the latter part of this section.

10.3.1 Analysing and presenting the issues

Based on the product description above and the product portfolio, the change drivers for the FAC machine can be considered as

- Closure size or type
- Bridge strength

A change in the closure size or type affects almost all change elements. The second change driver captures the activities to adjust blade cutting depth, which is often necessary to achieve the desired bridge strength. Overall 265 individual change elements were identified, of which 115 are functional CEs. The list of change elements is presented in the Appendix (Figure 14.2).

The changeover activities related to these CEs were subsequently identified (see Figure 10.5). As there is no real machine to this design the changeover times had to be estimated. Two different versions of changeover time estimates are here briefly compared. As part of their first generation redesign CROWN's engineers performed their own estimation exercise. In this approach the times were mostly derived by technicians with experience on similar equipment. As most operations during the FAC changeover are either assembly or disassembly operations the Design for Assembly (DFA) (Boothroyd et al., 1994) method was used for comparison with CROWN's estimates. For non-assembly and non-disassembly operations the CROWN estimates were used. The results of both estimations are shown in Table 10.1. For further details on the changeover activities and their associations to change elements see Appendix (Figure 14.1).

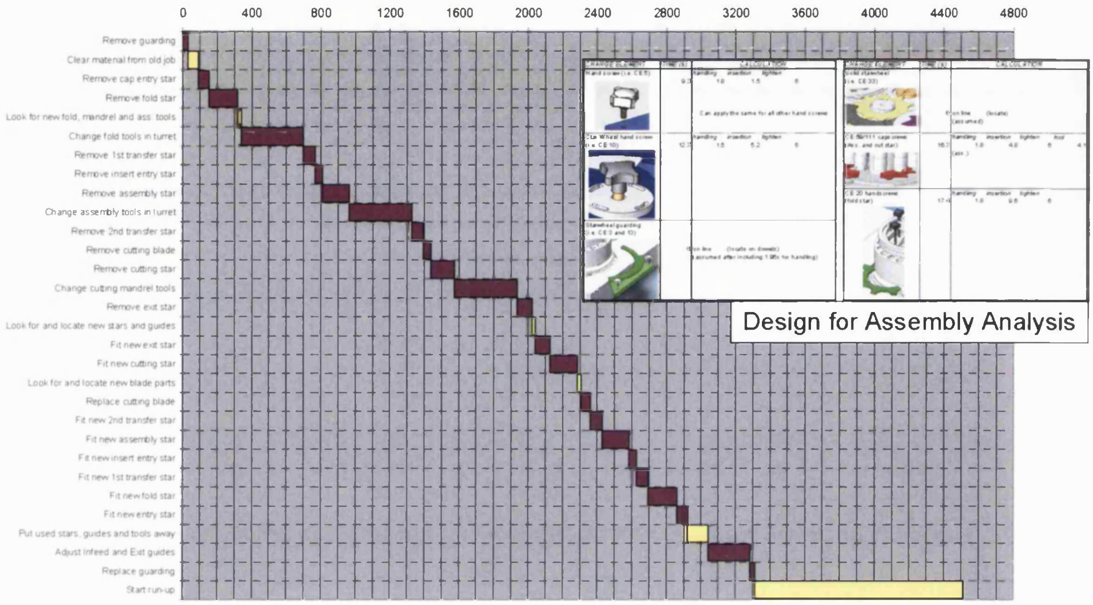


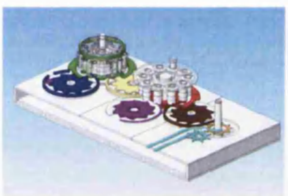
Figure 10.5 Detailed analysis of change elements and related changeover activities with DFA (Drawings printed with permission of CROWN Technology)

Table 10.1 Comparison of estimates from CROWN engineers with DFA estimates

	CROWN	DFA
Pure design analysis:	216 min	51 min
Incl. secondary tasks:	240 min	75 min

The DFA estimates are for manual assembly operations in mass manufacturing environments. The times achieved for assembly activities during a changeover are likely to be longer than the estimated DFA times as changeover tasks lack similar routine and repetition. Equally, CROWN estimates are likely to incorporate a margin to allow for all sorts of unexpected events. Thus, in reality the changeover times most likely lie between the two values. The advantage of using DFA estimates was that it allowed correlation between DFA and CROWN times. This would then allow making a better judgment on achievable changeover times when evaluating improvement concepts with DFA. For comparison, a first test changeover carried out on the newly build FAC machine took about 80min.

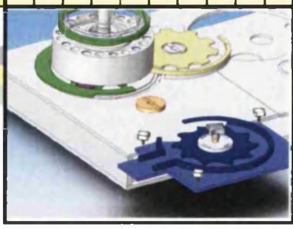
Using the change drivers identified earlier, changes can be decomposed into required changes to the change elements. Figure 10.6 shows what role the change elements play for specific change drivers for the folding operation. Based on the relationships between the CDs and the CEs a Change Driver Flow-down graph can be drawn. This is shown in Figure 10.7.



CHANGE DRIVERS		Cap Entry									
		1	2	3	4	5	6	7	8	9	10
Product Parameters	Values	Cap entry star wheel guide (40mm cap)	Cap entry star wheel guide (63mm cap)	Cap entry star wheel guide (82mm cap)	Cap entry star wheel guide (bespoke size)	4 hand screws for plate mounted guide	Cap entry star wheel (40mm)	Cap entry star wheel (63mm)	Cap entry star wheel (82mm)	Cap entry star wheel (bespoke size)	Cap entry star wheel hand screw
Closure type (diameter mm)	40	A				C	A				C
	63		A			C		A			C
	82			A		C			A		C
Tamper band cut depth	Var.										

CHANGE DRIVERS		Fold Operation																
		11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Product Parameters	Values	Fold turret guide - 2 halves (40mm)	Fold turret guide - 2 halves (63mm)	Fold turret guide - 2 halves (82mm)	Fold turret guide - 2 halves (bespoke size)	4 hand screws for fold turret guide	Fold star wheel - split (40mm)	Fold star wheel - split (63mm)	Fold star wheel - split (82mm)	Fold star wheel - split (bespoke size)	6 hand screws (3 each side) through turret	Fold Tools x10 (40mm)	Fold Tools x10 (63mm)	Fold Tools x10 (82mm)	Fold Tool x10 (bespoke size)	Collet half (assuming same for each fold tool)	Collar to pinch collet to fold tool	Method for fold turret adjust to make free spin
Closure type (diameter mm)	40	A				C	A				C	A				B	B	C
	63		A			C		A			C		A			B	B	C
	82			A		C			A		C			A		B	B	C
Tamper band cut depth	Var.																	

Established fasteners
No data
Assumption about element



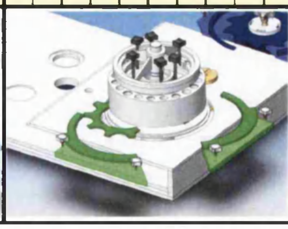


Figure 10.6 Change Driver-Change Element relationships for the Folding stage of the process. Illustrations printed with permission from Crown Technology

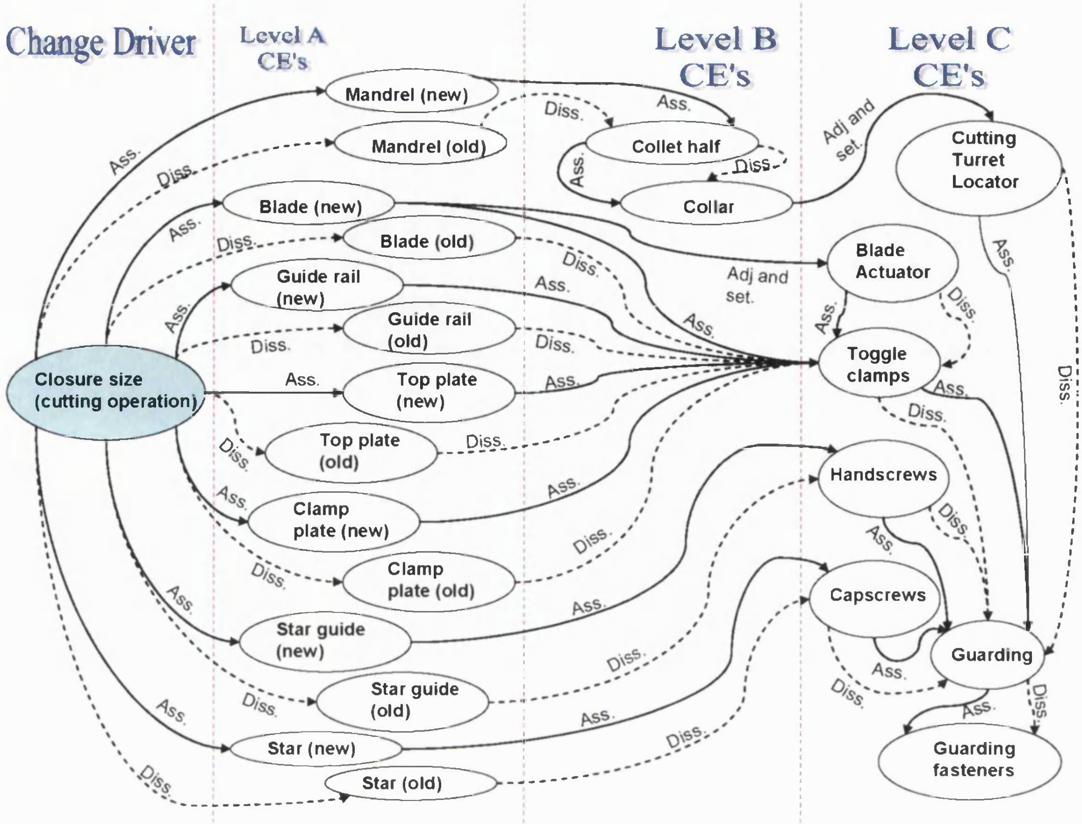


Figure 10.7 Change Driver Flow-down for the cutting stage

10.3.2 Identifying Improvement using Conceptual Re-Design

The Change Driver Flow-Down for the cutting operation is shown in Figure 10.7. However, this was not used to identify improvement opportunities as it was decided that focus of the author's and, his student, Dean Gale's work was the analysis of potential design alternatives for the FAC machine. Thus, it was decided to pursue a more fundamental re-design in order to assess possible improvement to changeover performance. The process as described by the revised DFC methodology in the previous Chapter was followed during this case study and the results are presented here (see Figure 10.8).

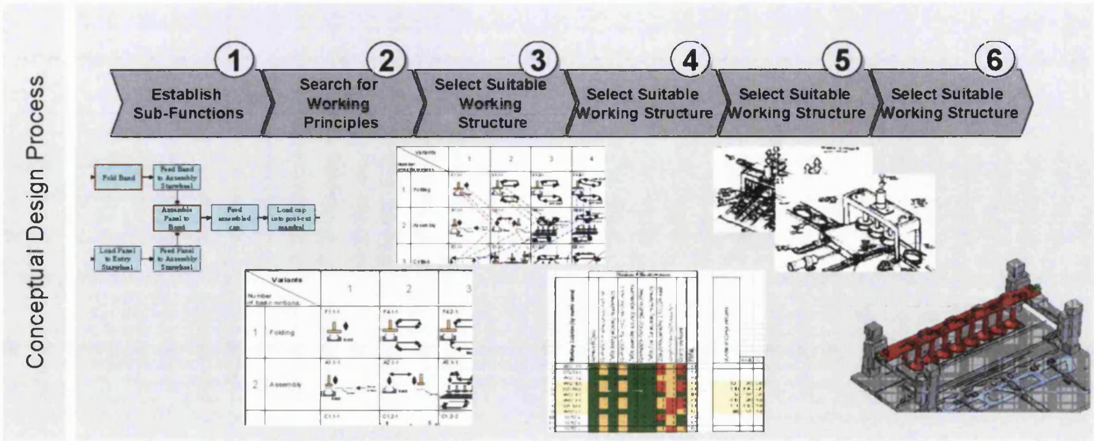


Figure 10.8 Overview of the conceptual design process followed for the 2nd Generation FAC machine

As part of this the search for working principles concentrated on the three main sub-functions, folding the plastic lip, assembling the metal panel to the plastic band and cutting. First, solution principles were identified based on the basic motions of tool and work piece holder as is illustrated in Figure 10.9 for the folding sub-function. Figure 10.10 shows a selection of solution principles which have been identified for the cutting operation. Solution principles for all the main sub-functions are shown in Figure 10.11.

The solution principles were then developed into working principles. Often several differing working principles were identified for individual solution principles. After a considerable number of working principles were identified for the main sub-functions, suitable combinations (working structures) were identified.

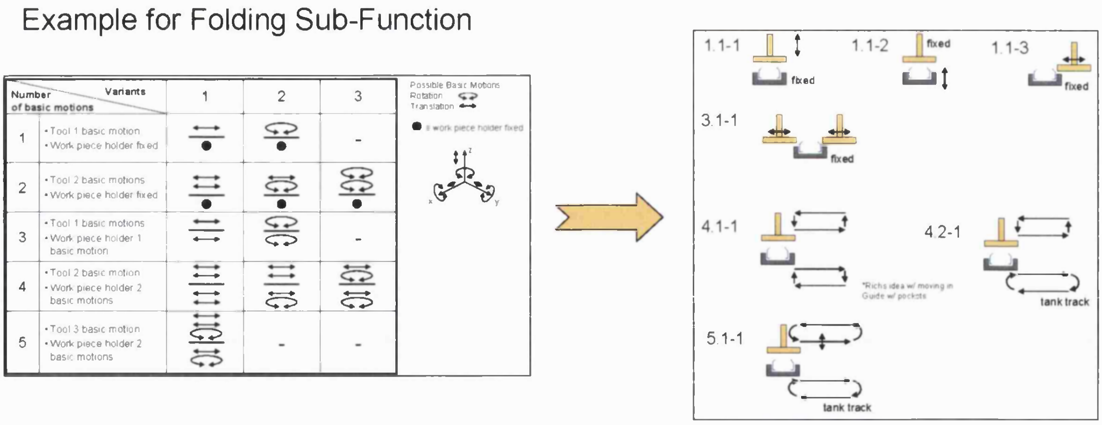


Figure 10.9 Possible basic motions for the folding sub-function and a selection of derived solution Principles

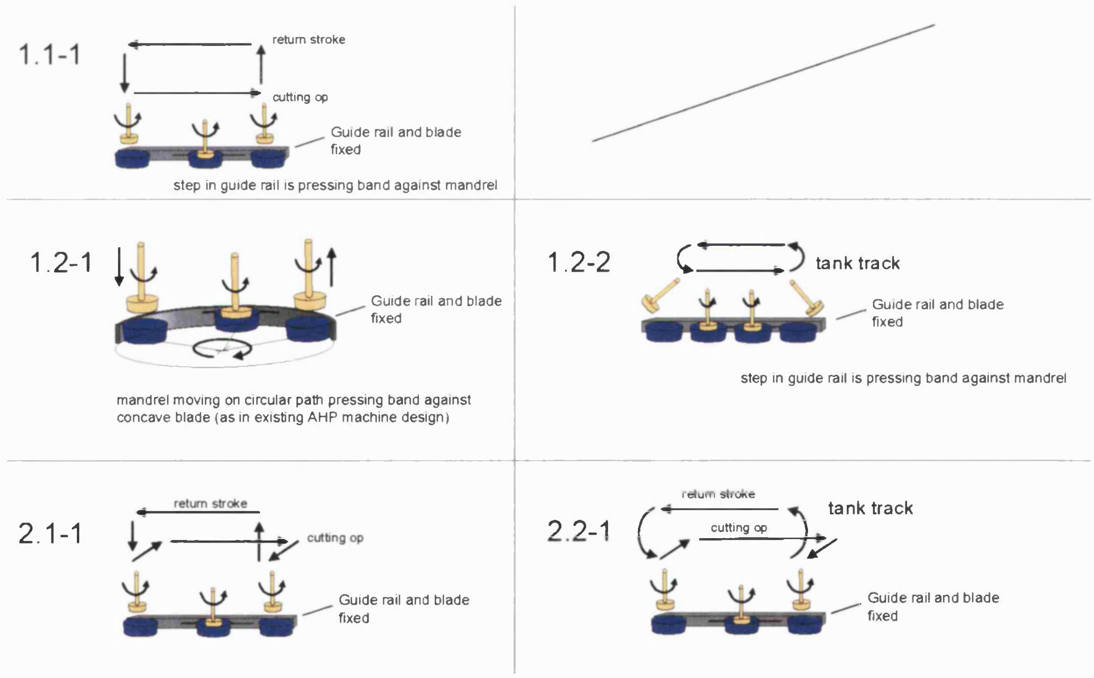


Figure 10.10 Solution principles for the cutting operation

Some of the possible combinations were ruled out from the start as they were considered technically or otherwise infeasible. Initially 15 feasible working structures were identified, which are based on the 9 different combinations of solution principles. More detailed analysis by the author, however, deemed different principle solutions as not feasible and the number of possible combinations of principle solutions was reduced to two (see Figure 10.11), which in turn reduced the number of working structures to six.

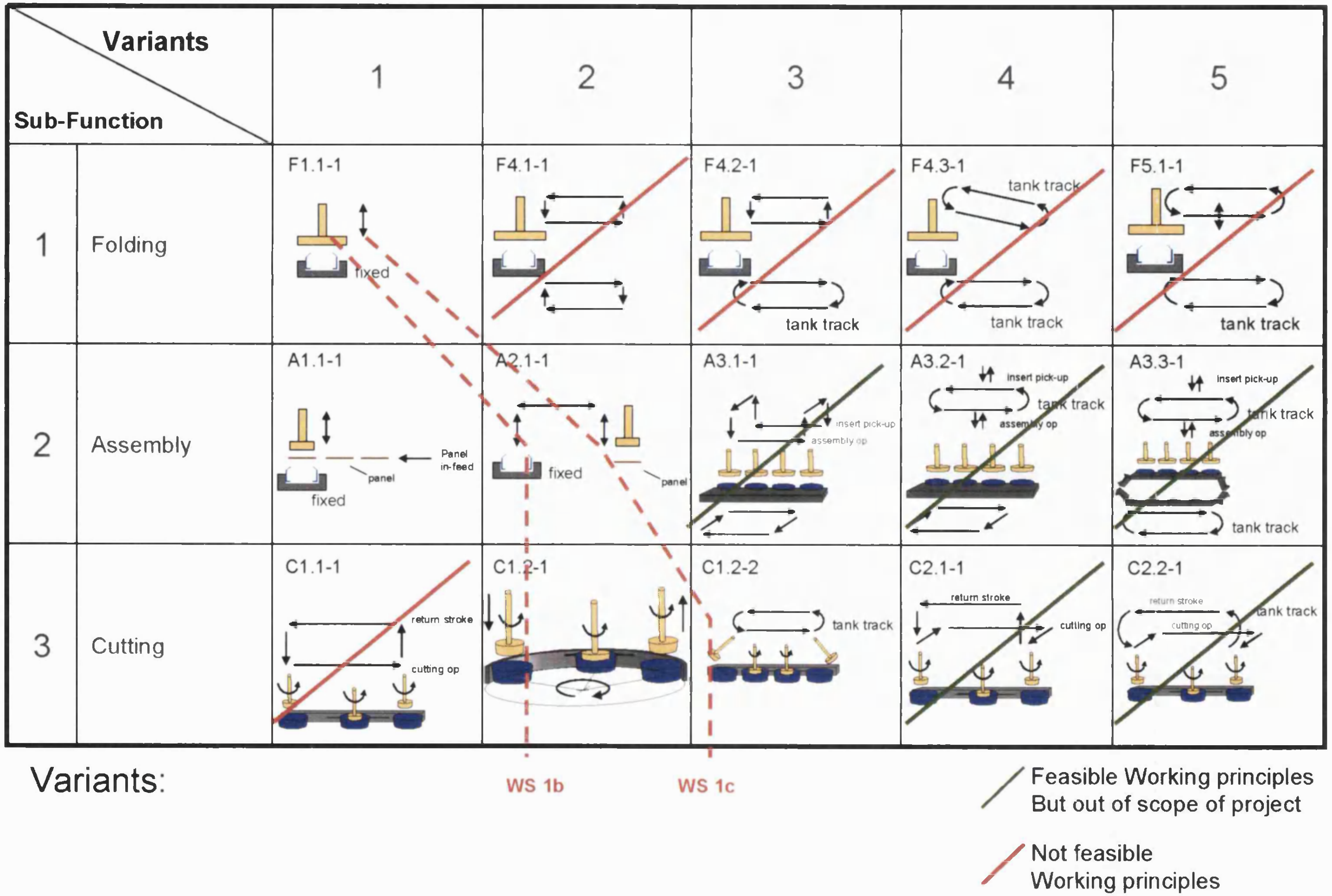


Figure 10.11 Feasible combinations of solution principles

After a further step of more detailed sketches the principal solution variants were formed and evaluation for the selection of a concept for further development was possible. As part of this evaluation, general engineering criteria were evaluated, but also a partial DFC analysis was carried out for each principal solution variant (Table 10.2).

Table 10.2 Evaluation of principal solution variants. Design effectiveness evaluation is based on Pahl and Beitz (1996)

		Design Effectiveness											DFC Analysis		
	Working Solution (by matrix name)	Achieve 600ppm	Controllable Folding operation infeed	Fulfils folding accuracy requirements	Controllable Assembly operation infeed	Fulfils assembly accuracy requirements	Controllable Post-Cut operation infeed	Fulfils Post Cut accuracy requirements	Size (contained within 2.1x1.12m area)	Simple to Design/Manufacture	Cost to impliment	**TOTAL**	Number of change element	Folding +Assembly	Cutting
1	WS1bX	2	1	2	1	2	2	2	0	1	0	13	131	*95*	*36*
2	WS1bY	2	1	2	1	2	2	2	0	1	0	13	136	*100*	*36*
3	WS1bZ	2	2	2	2	2	2	2	2	1	2	**19**	87	*51*	*36*
4	WS1cX	2	1	2	1	2	2	2	1	0	0	13	109	*95*	*14*
5	WS1cY	2	1	2	1	2	2	2	1	0	0	13	114	*100*	*14*
6	WS1cZ	2	2	2	2	2	2	2	2	0	1	17	**65**	*51*	*14*

Table 10.2 shows the results of the analysis of the principal solution variants. Principal solution variant 3 was chosen for further detailed design into a concept as it is likely to perform best in terms of general functional requirements and in terms of changeover as indicated by the evaluation. Initial DFC evaluation suggests that for this design approximately 87 CEs are required. Further design work was carried out on the chosen solution before a full DFC evaluation was carried out. Table 10.3**Error! Reference source not found.** shows the results of the detailed analysis. As can be seen, significant changeover performance improvements have been achieved. The DFA estimates suggest that the re-design can be changed over in about 25min, where secondary tasks are assumed unchanged. This is a 67% improvement on the previous changeover time.

Table 10.3 Comparison of DFC Evaluation of new concept with original design

	before	after
No of CE:	265	92
No of Functional CEs:	115	41
Pure design analysis (DFA):	51 min	8 min
Incl. secondary tasks (DFA):	75 min	25 min
Design Efficiency Index:	**43%**	**45%**
CO Activities Index:	**31%**	**32%**

From Table 10.3 it can be seen that the Design Efficiency and Changeover Activities Index only show small improvement. This is the case as the number of necessary CEs and the time of necessary changeover activities has changed. Because of the way the indices are defined, they can not show improvement when for example the number of necessary CEs changes significantly. This is likely to be the case when comparing design concepts based on different working principles.

10.4 Summary

A case study has been presented in which the revised DFC method was successfully applied during the conceptual design of a manufacturing machine. During the conceptual design process DFC analysis techniques were used for concept selection. The results of the DFC evaluation suggest that significant improvements of changeover performance can be achieved if a new way of manufacturing the closure range is adopted.

It was shown that DFC indices (Design Efficiency and Changeover Activities Index) do not necessarily illustrate the improvements achieved accurately, if a conceptual re-design is undertaken. The total number of CEs and the total estimated time of changeover activities, however, can still be used as indicators for good changeover performance.

11 Discussion and Future Work

This thesis makes a number of significant and original contributions to the areas of changeover improvement and the design of changeable manufacturing systems. In the area of changeover improvement a framework was developed which classifies overall improvement opportunities. In the area of the design of changeable manufacturing systems, a methodology was developed which facilitates the consideration of changeoverability when designing manufacturing systems. This chapter discusses the validation of the work carried out on both fields and suggests work that could be undertaken to further develop and extend the presented approaches.

11.1 Discussion of the 4P Framework for global Changeover Improvement Opportunities

A framework for global changeover improvement opportunities, namely the 4P framework, has been developed. The framework depicts the influence of organisation of people and practice, and the influence of design of process and products on changeover activities. The literature suggests that finding the right balance between design-led and organisational-led improvement initiatives is difficult and is – in the case of retrospective improvement programmes – often tending towards the low cost, quick-to-implement improvements (McIntosh *et al.*, 2001). Equally it is important that equipment designers are aware of the impact of their decisions on possible best practice operation of their equipment. Rather than a step-by-step method, the 4P framework gives a structure to global changeover improvement areas. A selection of small case studies is presented to support the importance of a balanced improvement effort between the 4 areas, people, practice, products and process.

11.2 Discussion of the Design for Changeover Methodology

A generic Design for Changeover (DFC) methodology has been developed in this thesis with the aim to provide systematic and structured design guidance for manufacturing equipment designers. As part of this, techniques were developed to describe changeover activity and subsequently evaluate changeover performance of manufacturing hardware. The validation of these techniques has been undertaken in a variety of ways and are discussed in the following sections.

11.2.1 Model

The modelling techniques developed in this thesis follow a modular approach. The core concept within the modelling techniques is the concept of Change Elements (CEs). These are what can conceptually be thought of as unstable elements of the manufacturing hardware, which are affected in some way by changeover activity. The work presented here has classified possible ways in which these CEs can be affected and has identified a set of changeover activities. Together they provide a means to describe what *changes* need to occur during a changeover and also what *activities* are required in order to undertake these changes. The modelling techniques can be used in retrospective and pro-active improvement environments. In retrospective improvement initiatives effort of changeover personnel can be attributed to individual changeover activities and change elements. The techniques can also be used, for example by OEMs, to estimate changeover times pro-actively. The usefulness of the developed techniques is shown by a number of case studies.

Furthermore a Change Driver Flow-Down (CDFD) graph has been developed which is an extension of the basic model described above. The CDFD allows the graphical representation of the required changes to CEs. It enables design teams to depict and understand the interdependencies between individual CEs.

11.2.2 Evaluation metrics

Based on the changeover modelling techniques a number of evaluation metrics have been proposed. These measures concern the evaluation of the influence of product variety on CEs and the effort and time required for changeover activities. The total time of changeover activities is representing the changeover duration and is the most accurate measure, but the case studies have also shown that a lower number of CEs is a good indicator for a better design when comparing different improvement options. This is shown in Table 11.1 which compares these two measures for a number of case studies and selected improvement options within these. The results suggest that reduction in the number of CEs is most likely to indicate a minimum improvement in terms of changeover time. This is important as this is a measure which can easily be derived even in early stages of the equipment design, as has been shown in case study 3.

Table 11.1 Compiled results of the evaluation of a number of case studies

			Duration/time units			Change Elements		
Case Study		Improvements	before	after	%	before	after	%
1	Shopping Trolley	Weld station	807	397	51%	27	11	60%
2	Closure Assy	2nd Gen FAC Machine	75	25	67%	265	92	65%
3	Bodymaker Beverage Can	Axial Adjustment	30	0.5	98%	4	1	75%
		Circumferential adj.	26	0.5	98%	3	1	67%
		Mandrel I – Sleeve	42	6	86%	2	1	50%
		Mandrel II – Telescopic Sleeve	42	2	95%	2	1	50%
		Mandrel III –Re-design datum	42	0	100%	2	0	100%
4	University of Bath Changeover Game		32	3.5	98%	29	14	51%

11.2.3 Design Guidance

The DFC methodology developed in this thesis provides systematic and structured design guidance. The provided guidance is based on the modelling techniques developed, such as change elements, changeover activities and the Change Driver Flow-Down. But design guidance is also provided by the proposed analysis and evaluation measures, which help designers selecting the most promising improvement options.

A number of gaps in the design guidance provided by existing design methods for changeable manufacturing systems have been identified in Chapter 6. The thesis aims to address four selected gaps. The following is a discussion of these:

- **Isolation of influence of product variety on CEs:** The methodology supports the isolation of influence of product variety on CEs in two ways. First, a systematic improvement search approach is developed based on the Change Driver Flow-Down graph. The graph can be used to evaluate the grouping of individual CEs into larger CE-entities. This allows systematic exploration of the design space with the intent of isolating the influence of product variety on CEs. Second, the grouping of CEs is also encouraged by the minimum number of CEs design target of DFC

- **Reduction of interdependencies between product variety and CEs:** Design guidance is provided on the top level of the Change Driver Flow-Down. The methodical procedure of Step 6 of the original DFC methodology to explore improvement ideas provides a systematic approach to identify ways in which the functional CEs can be designed such that they are independent from influence of the product variety

- **Reduction of interdependencies between CEs:** Design guidance is also provided by the Change Driver Flow-Down where influences of one CE on another are clearly depicted. The exploration procedure as part of the DFC methodology provides the designer with a systematic approach of searching for ways to reduce the interdependencies between CEs through the hierarchical representation of CEs

- **Reduction of effort and time required:** This is supported by the fact that the modelling and evaluation techniques provide a basis for effort and time estimation early in the design process. Also, measured times from witnessed changeovers can be attributed to individual CEs and changeover activities. This allows designers to evaluation of different improvements options and selection of the most promising solutions

11.3 Future Work

Recommendations for future work are given in this section concerning the 4P framework developed in Chapter 5 and for the DFC methodology developed in Chapters 6-10.

11.3.1 4P Framework

Further work on the 4P Framework is required to understand in more detail the relationships between the different areas. This would benefit those concerned with improving changeover performance, be it retrospective improvement engineers or OEM designers. Also, within the 4P Framework little work has been done on product design for changeover or even the integrated design of product and processes for changeover.

11.3.2 DFC Methodology

Recommendations for future work concerning the DFC methodology can be made in three areas. First, the improvement and refinement of the DFC tools and methods developed in this thesis. Second, the development and integration of a financial benefit analysis technique. Third, the development of a DFC software tool based on the methods proposed during this research. Along with these further testing and validation of the developed techniques in an industrial environment would be required.

The following sections describe these areas of future work in detail:

Further research and refinement of the existing DFC tools and methods

1. To further develop an integrated model of product variation and its influence on manufacturing process hardware, change elements and related changeover activities. The key parameters influencing difficulty of changeover activities need to be identified. Design for Assembly has already identified key parameters

influencing difficulty of assembly activities and thus allows the estimation of assembly activities by assessing features of the product and its components. The key parameters for other changeover activities, such as setting, adjustment, checking and controlling, also need to be identified.

2. To define models to estimate the difficulty of the different changeover activities using the identified key parameters
3. To define models to estimate duration of different changeover activities based on estimated difficulty
4. To identify top level design rules and categorise design rules regarding the already identified improvement mechanisms (Reduce task count directly, Reduce CE count, Reduce task difficulty, Amend when task is completed)
5. To update and collect design examples and drawings supporting the design rules and improvement mechanisms

Assessment of financial benefits of improved changeover performance

There is a need for a financial benefit assessment tool for improved changeover performance. For this, existing mathematical models developed at the University of Bath (McIntosh *et al.*, 2001, Bado, 2005) and elsewhere need to be refined. Also, further areas where financial benefits can gained through improved changeover performance need to be investigated. The DFC methodolody enables the changeover to be analysed in detail at the design stage. Arguably it is then possible to estimate changeover performance and relate it to the cost of the proposed machine. Design teams would then be able to have realistic flexibility vs. capital cost trade off discussions at the design stage.

DFC Software tool

The application of the DFC methodology could be greatly improved if aided by a software tool, as it is the case for example with Design for Assembly. For the development of such a DFC software tool the following future work would be required:

1. To describe the developed DFC models in a standard modelling language such as UML, Express_G, STEP or OPM (Object Process Modelling)

2. To develop an expert system supporting improvement engineers with context driven design mechanisms, design rules and design examples
3. To implement a pilot computer-based approach

Testing and Validating

The DFC methodology presented in this chapter has already been applied within an industrial environment (Case Study 1, 3 and further Case Studies). However, further testing and validating through application is required. Besides validating the developed methods, application can also provide the required data for the other areas of recommended future work, such as the models for estimation of changeover activity difficulty, the financial benefit assessment tools and a possible DFC software tool.

12 Conclusion

The ongoing trend towards further micro-segmentation of consumer markets has resulted in an increased offering of product variety by manufacturing enterprises. Many modern manufacturing paradigms have been proposed and adopted in order to cost effectively satisfy customer needs for product individualisation and ready delivery. Changeover capability is prominent in such a time-based manufacturing environment, where successful companies have to be able to adapt swiftly to market turbulence and at the same time avoid the traditionally high unit costs associated with custom made or small volume products. Frequent switching of manufacture between different products and processes while minimising detriment to overall productivity and quality is central to these aims.

Changeover improvement has been a focus of attention for a number of years as the limitations of systems developed for the mass-manufacturing paradigm have become recognised. Based on an extensive literature review carried out in the field of changeover improvement a framework for overall changeover improvement opportunities was developed in this thesis (Chapter 5). The framework clearly depicts the influence of organisation of people and practice, and the influence of design of process and products on changeover activities. A selection of three small case studies is used to make clear the importance of a balanced improvement effort between the four areas, people, practice, products and process.

The main aim of this thesis is to develop a Design for Changeover (DFC) methodology to assist manufacturing equipment designers take into account changeoverability requirements during the original design and retrospective improvement of the manufacturing process. Even though a number of case studies and examples of good design practice can be found from the literature there is no formal design for changeover (DFC) methodology. Some design for changeover rules have been proposed (McIntosh, 1998, Van Goubergen and Van Landeghem, 2002), which can be used to generally direct equipment design. However, these design rules do not give full guidance since they do not provide means to assess what new equipment's changeover capabilities will be once in service. Equally the rules are unranked, where some rules will be liable to have a far greater impact. A novel and original DFC methodology has been developed and tested in this thesis to provide machine designers with a coherent and structured guidance as to how genuine rapid changeover performance may be incorporated at the design stage. As part of this methodology, modelling, evaluation and design guidance tools and techniques were developed.

The modelling techniques developed in this thesis follow a modular approach, where a key element is the concept of Change Elements (CEs). These are unstable elements of the manufacturing hardware, which are affected by changeover activity. The work presented here has classified possible ways in which these CEs can be affected and has identified a set of changeover activities. The Change Driver Flow-Down provides the user with a graphical and hierarchical representation of the identified CEs and changeover activities. Together they provide a means to describe what changes need to occur during a changeover and what activities are required in order to undertake these changes. The modelling techniques can be used in retrospective and pro-active improvement environments.

Based on the changeover modelling techniques a number of evaluation metrics have been proposed. These measures concern the evaluation of the influence of product variety on CEs and the effort and time required for changeover activities. A number of case studies, of which some are presented in this thesis, suggest that a low number of CEs of a manufacturing hardware is a good indicator for a good changeoverability.

The DFC methodology developed in this thesis provides systematic and structured design guidance. The provided guidance is based on the modelling concepts and techniques developed, such as Change Elements, changeover activities and the Change Driver Flow-Down. But design guidance is also provided by the proposed analysis and evaluation measures, which help designers selecting the most promising improvement options.

Furthermore, the original DFC methodology has been further enhanced by integrating conceptual design methods into the DFC methodology (Chapter 9). This allows the user to systematically broaden the design search space and undertake more radical redesign work.

This can simply be a further step in case no sufficient improvement was identified using the original DFC methodology. But beyond this it can be a second starting point for the DFC methodology, if new equipment is designed or a more radical re-design is undertaken. Using the DFC evaluation methods developed in this thesis it is then possible to select the most promising concept in terms of changeover performance.

The tools and techniques developed in this thesis have been validated in a number of case studies, three of which are described in detail in this thesis. The usefulness of the proposed methodology has also been validated through workshops, training sessions and presentation to industrial collaborators.

List of Publications

Journal Papers

Reik, M. P., McIntosh, R. I., Owen, G. W., Culley, S. J., and Mileham, A. R. (2006). "A formal Design for Changeover (DFC) Methodology. Part 1 - Theory and Background." Proceedings of the IMECHE - Journal of Engineering Manufacture - Part B, 220(8), 1225-1236.

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Owen, G. W., Culley, S. J., Giess, M. D., Mileham, A. R., Eldrigde, C., McIntosh, R. I. and Reik, M. P. (2006). "Identifying and addressing run-up losses during changeover." Submitted to European Journal of Operational Research.

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Book Chapters

Reik, M. P., McIntosh, R. I., Owen, G. W., Mileham, A. R., and Culley, S. J. (2006). "Design for Changeover (DFC)." Mass Customisation - Challenges and Solutions, T. Blecker and G. Friedrich, eds., Springer, New York.

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14 Appendix

14.1 Nomenclature

Adj	Adjustment (see changeover activities Section 7.1.4)
Ass	Assembly (see changeover activities Section 7.1.4)
CAA	Changeover Activities Analysis (Section 7.2.2)
CE	Change Element. In general a CE can be a Product CE (PCEs) or a Equipment CE (ECEs) as defined in Section 7.1.3. For this thesis, however, PCEs are not considered any further and the concepts of CEs and ECEs are used interchangeably for simplicity (see Section 7.1.5 for more details).
CC	Checking and Controlling (see changeover activities Section 7.1.4)
Disass	Disassembly (see changeover activities Section 7.1.4)
DEA	Design Efficiency Analysis (Section 7.2.1)
DFX	Design for X
DFA	Design for Assembly
DFE	Design for Environment
DFC	Design for Changeover
ECE	Equipment Change Element, a CE which is part of the equipment as defined in Section 7.1.3.
F-ECE	Functional Equipment Change Element
Set	Setting (see changeover activities Section 7.1.4)
PCE	Product Change Element, a CE which is a product or raw material. This is a particular case of CEs which is not considered in the methodology developed in this thesis
PS-ECE	Primary Equipment Change Element
SS-ECE	Secondary Equipment Change Element
4P	The 4P Framework of People, Practice, Products and Process

14.2 Case Study 3 - DFC Analysis of 1st Generation Redesign

No.	CHANGEOVER TASK	TASK TIME (s)	CHANGEOVER ACTIVITIES A	B	C	D	E	F
1	Remove guarding	30	Remove fasteners CE 125 20	Lift guarding CE 124 10				
2*	Clear material from old job	60	Clear lines 60					
3	Remove cap entry star (and guides)	61.9	Remove 4 guide handscrews CE 5 37.2	Remove guides CE 1-3 6	Remove centre handscrew CE 10 12.7	Remove starwheel CE 6-8 6		
4	Remove fold star (and guides)	165.6	Remove 4 guide handscrews CE 15 37.2	Remove guides CE 11-13 12	Remove 6 star handscrews CE 20 104.4	Remove star halves CE 16-18 12		
5*	Look for new fold, mandrel and ass. Tools	20	Collect 30 tools 20					
6	Change fold tools in turret (10 off)	360.6	Lift collars over collets CE 26 16.3	Remove collets and tools CE 21-23 and 25 129	Fit collets and tools (new) CE 21-23 and 25 129	Drop collars down CE 26 16.3	Adjust turret (x10) CE 27 70	
7	Remove 1st transfer star (and guides)	67.9	Remove 4 guide handscrews CE 32 37.2	Remove guides CE 28-30 12	Remove centre handscrew CE 37 12.7	Remove starwheel CE 33-35 6		
8	Remove insert entry star (and guides)	43.3	Remove 2 guide handscrews CE 42 18.6	Remove guide CE 38-40 6	Remove centre handscrew CE 47 12.7	Remove starwheel CE 43-45 6		
9	Remove assembly star (and guides)	156.04	Remove 2 guide handscrews CE 52 18.6	Remove guide CE 48-50 6	Remove 4 capscrews CE 59 66.8	Remove star halves CE 55-57 12	Remove 3 sensor screws CE 54 47.01	Remove sensor CE 53 5.63
10	Change assembly tools in turret (10 off)	360.6	Lift collars over collets CE 65 16.3	Remove collets and tools CE 60-62 and 64 129	Fit collets and tools (new) CE 60-62 and 64 129	Drop collars down CE 65 16.3	Adjust turret (x10) CE 66 70	
11	Remove 2nd transfer star (and guides)	67.9	Remove 4 guide handscrews CE 71 37.2	Remove guides CE 67-69 12	Remove centre handscrew CE 76 12.7	Remove starwheel CE 72-74 6		
12	Remove cutting blade	44.26	Release toggle clamps (2 off) CE 101 4.26	Remove 4 components CE 85-101 40				
13	Remove cutting star (and guides)	136.8	Remove 2 guide handscrews CE 106 18.6	Remove guide CE 102-105 6	Remove 6 capscrews CE 111 100.2	Remove star halves CE 107-109 12		
14	Change cutting mandrel tools (10 off)	360.6	Lift collars over collets CE 83 16.3	Remove collets and tools CE 78-80 and 82 129	Fit collets and tools (new) CE 78-80 and 82 129	Drop collars down CE 83 16.3	Adjust turret (x10) CE 84 70	
15	Remove exit star (and guides)	86.5	Remove 6 handscrews CE 118 55.8	Remove all guiding (2 off) CE 114-116 12	Remove centre handscrew CE 123 12.7	Remove starwheel CE 119-121 6		
16*	Look for and locate new stars and guides	20	Collect 8 stars and the guides 20					
17	Fit new exit star (and guides)	86.5	Place and locate star CE 119-121 6	Screw in centre handscrew CE 123 12.7	Place guiding on dowels CE 114-116 12	Place 6 handscrews CE 118 55.8		
18	Fit new cutting star (and guides)	156.8	Place and locate star halves CE 107-109 12	Screw in 6 capscrews CE 111 100.2	Place guiding on dowels CE 102-105 6	Place 2 handscrews CE 106 18.6	Alter motor speeds CE 113 20	
19*	Look for and locate new blade parts	20	Collect 4 blade parts 20					
20	Replace cutting blade	54.26	Place 4 components CE 85-101 40	Move blade actuator CE 112 10	Close toggle clamps (2 off) CE 101 4.26			
21	Fit new 2nd transfer star (and guides)	67.9	Place and locate star CE 72-74 6	Screw in centre handscrew CE 76 12.7	Place guiding on dowels CE 67-69 12	Place 4 handscrews CE 71 37.2		
22	Fit new assembly star (and guides)	156.04	Place and locate star halves CE 55-57 12	Screw in 4 capscrews CE 59 66.8	Place guiding on dowels CE 48-50 6	Place 2 handscrews CE 52 18.6	Place sensor CE 53 5.63	Screw in 3 screws CE 54 47.01
23	Fit new insert entry star (and guides)	43.3	Place and locate star CE 43-45 6	Screw in centre handscrew CE 47 12.7	Place guiding on dowels CE 38-40 6	Place 2 handscrews CE 42 18.6		
24	Fit new 1st transfer star (and guides)	67.9	Place and locate star CE 33-35 6	Screw in centre handscrew CE 37 12.7	Place guiding on dowels CE 28-30 12	Place 4 handscrews CE 32 37.2		
25	Fit new fold star (and guides)	165.6	Place and locate star halves CE 16-18 12	Screw in the 6 CE 20's CE 20 104.4	Place guiding on dowels CE 11-13 12	Place 4 handscrews CE 15 37.2		
26	Fit new entry star (and guides)	61.9	Place and locate star CE 6-8 6	Screw in centre handscrew CE 10 12.7	Place guarding on dowels CE 1-3 6	Place 4 handscrews CE 5 37.2		
27*	Put used stars, guides and tools away	120	Place in store 120					
28	Adjust Infeed and Exit guides	240	Adjust Infeed Guide CE 126 120	Adjust Exit Guide CE 127 120				
29	Replace guarding	30	Lower guarding CE 124 10	Place fasteners CE 125 20				
30*	Start run-up	1200	Initialise run-up 600	refine task 21 600				
		75.20	minutes					
		51.20	minutes without work practice					

* Work practice tasks

Figure 14.1 Breakdown of Changeover tasks into changeover activities

	CHANGE ELEMENTS			TIMES						
	ELEMENT	No. OFF	CE number	Dissassembly	Setting	Assembly	Operation time per CE	Operation time for all CE's	Nec. CE's	Nec. CE's time
Cap Entry	**Cap entry star (old)**	1	6-8	6			6	6	1	6
	Cap entry guides (old)	1	1-3	6			6	6	2	12
	Cap entry star (new)	1	6-8			6	6	6	1	6
	Cap entry guides (new)	1	1-3			6	6	6	2	12
	Handscrews (guide)	4	5	9.3		9.3	18.6	74.4	0	0
	Handscrew (star)	1	10	12.7		12.7	25.4	25.4	0	0
Fold Operation	**fold star halves (old)**	2	16-18	6			6	12	2	12
	fold guides (old)	2	11-13	6			6	12	2	12
	fold star halves (new)	2	16-18			6	6	12	1	6
	fold guides (new)	2	11-13			6	6	12	2	12
	Handscrews (guide)	4	15	9.3		9.3	18.6	74.4	0	0
	Handscrews (star)	6	20	17.4		17.4	34.8	208.8	0	0
	Fold tools (old)	10	21-23	6.3			6.3	63	10	63
	Fold tools (new)	10	21-23			6.3	6.3	63	10	63
	Fold collet	10	25	6.6		6.6	13.2	132	0	0
	Fold collar	10	26	1.63		1.63	3.26	32.6	0	0
	Turret adjust	10	27		7		7	70	0	0
1st Transfer	**1st transfer star (old)**	1	33-35	6			6	6	1	6
	1st transfer guides (old)	2	28-30	6			6	12	2	12
	1st transfer star (new)	1	33-35			6	6	6	1	6
	1st transfer guides (new)	2	28-30			6	6	12	2	12
	Handscrews (guide)	4	32	9.3		9.3	18.6	74.4	0	0
	Handscrew (star)	1	37	12.7		12.7	25.4	25.4	0	0
Insert Entry	**Insert entry star (old)**	1	43-45	6			6	6	1	6
	Insert entry guide (old)	1	38-40	6			6	6	1	6
	Insert entry star (new)	1	43-45			6	6	6	1	6
	Insert entry guide (new)	1	38-40			6	6	6	1	6
	Handscrews (guide)	2	42	9.3		9.3	18.6	37.2	0	0
	Handscrew (star)	1	47	12.7		12.7	25.4	25.4	0	0
Assembly Operation	**Assembly star halves (old)**	2	55-57	6			6	12	2	12
	Assembly guide (old)	1	48-50	6			6	6	1	6
	Assembly star halves (new)	2	55-57			6	6	12	2	12
	Assembly guide (new)	1	48-50			6	6	6	1	6
	Guide rail sensor	1	53	5.63		5.63	11.26	11.26	0	0
	Sensor position screws	3	54	15.67		15.67	31.34	94.02	0	0
	Handscrews (guide)	2	52	9.3		9.3	18.6	37.2	0	0
	Capscrews (star)	4	59	16.7		16.7	33.4	133.6	0	0
	Assembly tools (old)	10	60-62	6.3			6.3	63	10	63
	Assembly tools (new)	10	60-62			6.3	6.3	63	10	63
	Assembly collet	10	64	6.6		6.6	13.2	132	0	0
	Assembly collar	10	65	1.63		1.63	3.26	32.6	0	0
	Turret adjust	10	66		7		7	70	0	0
2nd Transfer	**2nd transfer star (old)**	1	72-74	6			6	6	1	6
	2nd transfer guides (old)	2	67-69	6			6	12	2	12
	2nd transfer star (new)	1	72-74			6	6	6	1	6
	2nd transfer guides (new)	2	67-69			6	6	12	2	12
	Handscrews (guide)	4	71	9.3		9.3	18.6	74.4	0	0
	Handscrew (star)	1	76	12.7		12.7	25.4	25.4	0	0
Cutting Operations	**Cutter star halves (old)**	2	107-109	6			6	12	2	12
	Cutter guide (old)	1	102-105	6			6	6	1	6
	Cutter star halves (new)	2	107-109			6	6	12	2	12
	Cutter guide (new)	1	102-105			6	6	6	1	6
	Gearbox speed	1	113		20		20	20	0	0
	Handscrews (guide)	2	107	9.3		9.3	18.6	37.2	0	0
	Capscrews (star)	6	111	16.7		16.7	33.4	200.4	0	0
	Cut mandrel tools (old)	10	78-80	6.3			6.3	63	10	63
	Cut mandrel tools (new)	10	78-80			6.3	6.3	63	10	63
	Cut mandrel collet	10	82	6.6		6.6	13.2	132	0	0
	Cut mandrel collar	10	83	1.63		1.63	3.26	32.6	0	0
	Turret adjust	10	84		7		7	70	0	0
	Toggle clamps	2	101	2.13		2.13	4.26	8.52	0	0
	Blade (old)	1	85-87	10			10	10	1	10
	Blade (new)	1	85-87			10	10	10	1	10
	Clamp plate (old)	1	88-91	10			10	10	1	10
	Clamp plate (new)	1	88-91			10	10	10	1	10
	Guide rail (old)	1	93-95	10			10	10	1	10
	Guide rail (new)	1	93-95			10	10	10	1	10
	Top plate (old)	1	97-99	10			10	10	1	10
	Top plate (new)	1	97-99			10	10	10	1	10
	Blade actuator	1	112		10		10	10	0	0
Cap Exit	**Cap exit star (old)**	1	119-121	6			6	6	1	6
	Cap exit guides (old)	2	114-116	6			6	12	2	12
	Cap exit star (new)	1	119-121			6	6	6	1	6
	Cap exit guides (new)	2	114-116			6	6	12	2	12
	Handscrews (guide)	6	118	9.3		9.3	18.6	111.6	0	0
	Handscrew (star)	1	123	12.7		12.7	25.4	25.4	0	0
Misc.	Guarding	1	124	10		10	20	20	0	0
	Guarding fasteners	1	125	20		20	40	40	0	0
	Infeed guide	1	126		120		120	120	1	120
	Exit guide	1	127		120		120	120	1	120
	TOTAL	265	CE's					3072.2	117	980
								seconds	ec. CE's	seconds
								51.20		16.333333
								minutes		minutes
							Design Efficiency	44.15	%	
							c/o activities index	31.90	%	

Figure 14.2 DFC Analysis (using DFA time estimates